

18th INTERNATIONAL CONFERENCE ON ENGINEERING & NATURAL SCIENCES

EDITORS

Prof. Dr. Tolga KARAKÖY
Prof. Dr. Ercan CEYHAN

CONFERENCE PROCEEDINS BOOK

18th INTERNATIONAL CONFERENCE ON ENGINEERING & NATURAL SCIENCES

LIBERTY PUBLISHING HOUSE

Date: 21.12.2025
Water Street Corridor New York, NY 10038
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adopted by Mariam Rasulan

ISBN: 979-8-89695-279-4

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18th INTERNATIONAL CONFERENCE ON ENGINEERING & NATURAL SCIENCES

November 27-29, 2025
Kyrenia, TRNC

PROCEEDINGS BOOK
(Abstracts & Full Texts)

EDITOR

Prof. Dr. Tolga KARAKÖY
Prof. Dr. Ercan CEYHAN

ISBN: 979-8-89695-279-4

DOI: https://doi.org/10.5281/zenodo.18009064

ISSUED: December 21, 2025

18th INTERNATIONAL CONFERENCE ON ENGINEERING & NATURAL SCIENCES

EVALUATION PROCESS and POLICIES

All applications have undergone double blind peer review process. In addition, each paper was accepted and the process of publishing in the book was carried out through editorial oversight. The published papers were presented and discussed at the meeting.

Full texts and abstracts published in accordance with the Symposium Policy have been prepared in accordance with ethical rules and APA standards. Authors of all papers are both ethically and legally responsible.

PARTICIPANTS COUNTRIES

Türkiye, Albania, Algeria, Azerbaijan, Bangladesh, Bulgaria, Ethiopia, Georgia, India, Indonesia, Iran, Kazakhstan, Malaysia, Morocco, Nigeria, Pakistan, Philippines, Saudi Arabia, Slovenia, Sri Lanka, Uganda, Ukraine

TOTAL ACCEPTED ARTICLES: 306

The Number of Accepted Papers from Türkiye: 179
The Number of Accepted Full Papers from Other Countries: 214
The Number of Total Papers: 393

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18th INTERNATIONAL CONFERENCE ON ENGINEERING & NATURAL SCIENCES

November 27-29, 2025 / Kyrenia, TRNC

CONGRESS PROGRAM

Online (with Video Conference) Presentation

Meeting ID: 929 9691 8209 / Passcode: 272829

https://zoom.us/j/92996918209?pwd=zglIR6LH5JbLaMUMAHOHvAIEfxmRx1.1



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- The Zoom application is free and no need to create an account.
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- The application works on tablets, phones and PCs.
- Moderator - responsible for the presentation and scientific discussion (question-answer) section of the session.

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- Moderator is responsible for ensuring the smooth running of the presentation, managing the group discussion and dynamics.
- **Before you login to Zoom please indicate your name_surname and HALL number, exp. Hall 1, Gülen**

-Opening Ceremony-

Kyrenia Local Time: 09:30-09:50
Veue: The Olive Tree Hotel Meeting Room

***

Dr. Öğr. Üyesi Yeter ÇİLESİZ
(Sivas Science and Technology University)
CONFERENCE COORDINATOR

***

Prof. Dr. Tolga KARAKÖY
(Sivas Science and Technology University)
CONFERENCE CO-CHAIR

***

Prof. Dr. Ercan CEYHAN
(Konya Selçuk University)
CONFERENCE CO-CHAIR

-Coffee Break-

Kyrenia Local Time: 09:50-10:00

28.11.2025
Kyrenia Local Time: 10:00-12:00

(All speakers required to be connected to the session 15 min before the session starts)
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IN-PERSON SESSION

Veue: The Olive Tree Hotel
HALL-1

MODERATOR: Hatice BEKCİ

AUTHOR	AFFILITION	ABSTRACT TITLE
Yeşim Sağlam Özkan Yeliz Kara Ali Berkan Bektaş	*Bursa Uludağ University*	On Neighborhood-Based Topological Indices In Quantitative Structure–Activity Relationship Analysis Of Some Fda-Approved Anticancer Agents
Chukwudi Gracious Maduka	*Cyprus International University*	Lightweight Machine Learning For Ddos Attack Detection In Resource-Constrained Smart Home Environments: A Hybrid Approach Using Feature Selection And Comparative Model Analysis
İrem Küçükoğlu Niyazi Ugur Kockal	*Alanya Alaaddin Keykubat University*	An Approach To The Deflection Due To Distributed Loading On Beams By Using Hermite-Type Polynomials
Niyazi Ugur Kockal Alp Cesur	*Akdeniz Üniversitesi*	Effect Of Gamma Rays Applied To Polymer Modified Mortars On Physico-Mechanical Properties
Suha Orçun Mert Ali Ayazseven	*İskenderun Teknik University*	Comparison Of Discharge Analysis Of Supercapacitor And Lithium Polymer Batteries Under Constant Load In Terms Of Efficiency
Aslı Kaçar Zekiye Erdoğan Gökhan Erdoğan Baran Aslan Aylin Kabaş Ibrahim Çelik Selman Uluışık	*Akdeniz University*	Assessment Of Tetranychus Urticae Tolerance In Tomato Lines Derived From Solanum PennellII (LA0716)
Ayşen Bulancak Mikail Baylan	*Cyprus International University*	The Effects Of Climate Change On Poultry Production And Solutions
Yasemin Gümüştaş Mikail Baylan Aziz Gül	*Çukurova University*	Determination Of Lithium Chloride Residue Levels In Honey Used For The Control Of Varroa Destructor In Honeybees (Apis Mellifera)
Hatice Bekci	*Kayseri University*	Biological Activities Of Vinegars
Tolga Karaköy Ömer Sözen Yeter Çilesiz	*Sivas University Of Science And Technology*	Assessment Of Morphological Adaptation Traits Of Selected Bread Wheat Genotypes Under Changing Climatic Conditions In Sivas

28.11.2025
Kyrenia Local Time: 10:00-12:00

(All speakers required to be connected to the session 15 min before the session starts)
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IN-PERSON SESSION

Veue: The Olive Tree Hotel
HALL-2

MODERATOR: Yeliz KARA

AUTHOR	AFFILITION	ABSTRACT TITLE
Yeliz Kara Yeşim Sağlam Özkan Ali Berkan Bektaş	*Bursa Uludağ University*	Qspr Analysis Of Anticancer Compounds Using Neighborhood Sombor And Related Topological Indices
Ali Keleş	*Yüzüncü Yıl University*	Some Edible Macrofungi Detected In Van Yüzüncü Yıl University Campus And Surrounding Area (Van, Turkey)
Mehmet Arif Saltan Alperen Aykun Volkan Soylu Doğukan Korucu Melih Turan Sevindik Mustafa Bekir Acar	*Milli Savunma University*	Investigation Of The Combustion Efficiency Of A Natural Gas-Hydrogen Mixture In A Combustion Chamber Using Computational Fluid Dynamics
Muhammet Ali Gündeşli Murat Manav	*Kahramanmaraş İstiklal University*	Active Compound Losses And Alterations In Drug Preparation From Medicinal Plants: Causes And Prevention Strategies
Muhammet Ali Gündeşli	*Kahramanmaraş İstiklal University*	Quality Control Parameters And Standards In The Drug Preparation Process Of Medicinal Plants
Nurten Yılmaz Fatih Özoğul	*Cukurova University*	Postbiotic Organic Acids Produced By Food- And Seafood-Isolated Lab Strains: Chemistry, Functional Roles, And Health Implications
Elif Dağgeçen Çoskun Nurten Yılmaz Uğur Zülkadir Erdal Kuşvuran	*Cukurova University*	Antibiotic Resistance In Seafood-Derived Probiotic Strains: Mechanisms, Prevalence, And Safety Implications
Sertan Denizli Ezgi Yılmaz Göç	*Brisa Bridgestone Sabancı Tyre Manufacturing And Trading Inc.*	Optimization Of Lead Lug Ratio For Enhanced Traction And Wear Performance In Agricultural Vehicles
Oğuzhan Uygurlu Ezgi Yılmaz Göç	*Brisa Bridgestone Sabancı Tyre Manufacturing And Trading Inc.*	Relationship Of Rrc-Temperature-Speed On Truck And Bus Tires (22.5 Sizes)
Suat Vardar Turgut Tüzün Onay	*Boğaziçi University*	Investigation Of Microplastic Presence In Tap Waters In Istanbul
Emine Balı Selda Uzal Seyfi	*Selçuk University*	Evaluation Of General Characteristics Of Greenhouse Enterprises In Central Districts Of Adana Province
Yasemin Kocaman Selda Uzal Seyfi	*Selçuk University*	Contruction Of A Carbon Emission Density Map For Layer Hens Farms In Konya Province And Its Districts Via The Tier 1 Methodology

ONLINE SESSIONS

27.11.2025
Kyrenia Local Time: 09:00-11:00
Ankara Local Time: 10:00-12:00

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SESSION-1, HALL-1 / OTURUM-1, SALON-1

MODERATOR: Fatma Yıldız

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Mine Kılıç Birsel Demirel Gül Eda Kılınç	*Ondokuz Mayıs University*	The Role Of Phase Angle In Nutritional Status Assessment
Perihan Kızılkaya Birsel Demirel Gül Eda Kılınç	*Ondokuz Mayıs University*	Irritable Bowel Syndrome And Nutrition: Evidence-Based Approaches From Diagnosis To Treatment
Gizem Yılmaz Semra Alkan Türkuçar	*Alanya Alaaddin Keykubat University*	Investigation Of Cytotoxic And Apoptotic Effects Of Alchemilla Caucasica Buser Extracts On Human Mcf-7 Cell Line
Fatma Yıldız	*Alanya Alaaddin Keykubat University*	Neuroprotective Effect Of A Novel Benzimidazolium Derivative: An Approach Through Dnmt-Mediated Epigenetic Regulation
Şebnem Kuşvuran Fathia Mohamed Ali	*Çankırı Karatekin University*	Effects Of Nano-Silicon On Germination And Seedling Development Of Melon Genotypes Under Salt Stress
Şebnem Kuşvuran Fathia Mohamed Ali	*Çankırı Karatekin University*	Effects Of Nano-Silicon Applications On Growth, Yield, And Fruit Quality In Tomato (Solanum Lycopersicum L.) Under Salt Stress Conditions

27.11.2025
Kyrenia Local Time: 09:00-11:00
Ankara Local Time: 10:00-12:00

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SESSION-1, HALL-2 / OTURUM-1, SALON-2

MODERATOR: Sena Yaşar

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Muhammet Melih Memiş	*Çankırı Karatekin University*	Turbocharger System Radial Compressor Impeller Design
Ali Umut Şen	*Izmir Institute Of Technology*	Advanced Kinetic Modeling Of Bark Pyrolysis Using Distributed Activation Energy Models
Mert Ökten	*Manisa Celal Bayar University*	Integrated Assessment Of Photovoltaic, Reverse Osmosis, And Seawater Heat Pump Systems In The Context Of Energy And Water Sustainability: A Case Study For The Turkish Republic Of Northern Cyprus
Filiz Senyuzluler Adil Baykasoglu	*Dokuz Eylül University*	Toward An Uncertainty-Tolerant Electric Vehicle Recommendation System Via Weighted Axiomatic Design
Sena Yaşar Yusuf Özçatalbaş	*Gazi University*	Failures And Prevention Methods In Welded Joints Of Construction Machinery
Güven Nergiz K. Turgut Gürsel	*Dokuz Eylül University*	Coastal And Offshore Wind Turbine Types And Modelling
Oğuzhan Yılmaz K. Turgut Gürsel	*Dokuz Eylül University*	Analysis Of High-Speed Planning Boat Forms In Terms Of Step Design

27.11.2025
Kyrenia Local Time: 09:00-11:00
Ankara Local Time: 10:00-12:00

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SESSION-1, HALL-3 / OTURUM-1, SALON-3

MODERATOR: Mokesh Velraj

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Laila Ouardi Hasna Zinelabidine Abdelmajid Haddioui Hassane Boudad Abdelghani Bouchyoua Jamal Charafi	*University Of Sultan Moulay Slimane*	Cold Stress Responses In Grapevine: Comparative Morphophysiological And Biochemical Traits Of Three Cultivars
Sadiq M.S. Singh I.P. Ahmad M.M. Sani B.S.	*Federal University Dutse*	Digitalization And The New Semiotics Of Branding
Mokesh Velraj	*R.M.K. Engineering College*	Intelligent Solar Power Forecasting Using Hybrid Cnn-Lstm Architecture: An Iot-Enabled Embedded Systems Approach
R. Devadharshini W. Helen	*Bharath Institute Of Higher Education And Research*	Artificial Organs And 3d Bioprinting
Masudul Islam Khan Shajmin Akter	*Daffodil International University*	Mechanisms and Therapeutic Applications of the Antifungal Activity of Tea Tree Oil: A Comprehensive Review
Bilal Shah Dicky Muslim Raden Irvan Sophian	*Universitas Padjadjaran*	Geomechanics Of Andesitic Rock Units In The Gunung Geulis Area, Sumedang Regency, Indonesia
Mohamed Kadour Atouailaa Bader Boukili Arif Ahmed Abdelkhalk Aboulouard Mustapha Boulghalat Mohammed El Idrissi	*Sultan Moulay Slimane University*	Surveying Novel Pyrazine Acceptor Materials For Bulk Heterojunction Solar Cells: Computational Insights Into Photovoltaic Performance
Umma Nourin Sawon Nahidul Islam Hasan Samrat Hasibul Islam Shishir Al-Amin Sarker Jannatul Ferdoushi	*Iubat—International University Of Business Agriculture And Technology*	Predicting Air Quality: Machine Learning (Ml) Models For Pm2.5 Concentrations In Delhi, India

27.11.2025
Kyrenia Local Time: 09:00-11:00
Ankara Local Time: 10:00-12:00

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SESSION-1, HALL-4 / OTURUM-1, SALON-4

MODERATOR: Milos Rabrenovic

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Arulmozhi M Aishwarya S Bhavana B Deepika R Dhanvanthari S Vijayalakshmi A	*R.M.K. Engineering College*	Sort Smart: The Power Of Waste Segregation
Devesh R Dharsan G Immanuvel M Jai Shyam S Janaardan S Vijayalalkshmi A	*R.M.K. Engineering College*	Smart Grids And Renewable Energy Integration
Bairi Mani Ganesh Abdul Reyas A Akash R Arigaran S Barani Chandran S Vijayalakshmi A	*R.M.K. Engineering College*	Pollution: A Major Barrier To Sustainable Development
Zainib Razzaq Samreen Gul Khan Fozia Anjum Ayesha Saddiqa Mehr Un Nisa	*Government College University*	Novel 1,3,4-Oxadiazole Carbamothioates As Anticonvulsant Agents: From Synthesis And Molecular Docking To Electrophysiological Validation
Mohamed Bakır Abdelkader Youssefi Rachid Dakır Mouna El Wafı Younes El Koudıa	*Hassan First University*	Intelligent Highway Lane Changes: Enhancing Safety And Comfort Through Predictive Sensor Fusion And Trajectory Optimization
Milos Rabrenovic Monika Stojanova	*Montenegro Dance Sport Federation*	Dance As Athletic Performance: The Role Of Functional Food In Enhancing Dancer Health And Nutrition
Sowjanya D Sharada S	*Jawaharlal Nehru Technological University*	Process Intensification By Continuous Flow Microreactor For The Synthesis Of Sno 2 Nanoparticles Using Natural Reducing Agent

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Ankara Local Time: 10:00-12:00

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SESSION-1, HALL-5 / OTURUM-1, SALON-5

MODERATOR: Elza Bitsadze

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Kareena Saini Seema Rathee Jitender Kumar	*Mdu*	The Role Of Emotional Intelligence Training In Managerial Effectiveness
Ayesha Zulfiqar Farhana Naz Maryam Usman	*Lahore College For Women University*	Sustainable Retail Environments: A Design-Based Exploration Of Zero-Waste Grocery Stores
V. Ranjani R. Srinivasan R. Saravanan R. Devi N. Jayaramakani	*Bharath Institute Of Higher Education And Research*	Design And Development Of Oral Controlled Release Systems For Sustained Drug Delivery
Sunday Olorunlogbon Olorunnipa	*Quintessential College*	Assessing The Challenges And Consequences Of Executive Leadership Without Organizational Literacy: A Focus On Ceos From Non-Managerial Disciplines
Elza Bitsadze	*Akaki Tsereteli State University*	Intelligent Algorithms In Databases For Automated Decision-Making
Balasubramanian Chinnappan Kareemullah Hakim Noorullah Khan	*B.S.A Crescent Institute Of Science And Technology*	A Secure And Resilient Edge-Block-Chain Neural Network System For Industrial Pollution Monitoring Under Gprs Outages
Konok Chandro Roy M. Riju Khandaker M.N.H. Liton M.M. Rahman M.S.I. Sarker M.K.R. Khan	*University of Rajshahi*	Synthesis and Characterization of Li 2 ZnSnO 4 by Sol-Gel Method and First Principals Study
Shajib Shahrear Rajibul Akanda Foysal Hasan M. Aminul Haque	*Jagannath University*	A Comprehensive Investigation On Eggshell Powder As Natural Adsorbent For Methyl Orange Dye Removal: A Study Of Kinetics, Isotherm And Thermodynamics
Zaara Nabil Dahmani Jamila Skalli SouadAKTER Douir Allal	*Tofail University*	Influence of climatic factors and cropping system on the agronomic characteristics of olives (Olea Europaea L.) of the Moroccan Picholine variety cultivated in the olive-growing regions of Morocco

27.11.2025
Kyrenia Local Time: 11:30-13:30
Ankara Local Time: 12:30-14:30

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SESSION-2, HALL-1 / OTURUM-2, SALON-1

MODERATOR: Nalan Türköz Karakullukçu

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Nalan Türköz Karakullukçu	*Ondokuz Mayıs University*	Investigation Of The Effects Of Rubus Anatolicus Focke Extract On The Oxidative And Thermal Stability Of Biodiesel–Diesel Blends Using Gc–Ms And Dsc
Erdal Kocasüleyman Dursun Ekren	*Iskenderun Technical University*	Structural And Optical Properties Of Barium Doped Lanthanum Molybdate
Hatice Çiçekçi	*Epsan Plastik*	Development Of Hydrolysis Resistant Pa6.6 Composite Materials With Laser Transparency Suitable For Use In The Automotive Industry
Zeynep Sıla Tırpancı	*Epsan Plastik*	Production Of Custom-Colored Pbt/Rpet Blends Suitable For Electrical And Electronic Applications
Safarova Terane Qasim Rahimova Konul Elbrus	*Azerbaijan State University*	İntegration Of Structurally Diverse Fibrous Elements And Polymeric Matrices İn The Development Of Composite Materials
Safarova Terane Qasim	*Azerbaijan State University*	The Structure And Fabrication Method Of A Wear-Resistant Textile Incorporating Multilayer And Layered-Frame Interlacing Elements
Osman Özdemir Servet Soygüder	*Ankara Yıldırım Beyazıt University*	Field-Oriented Application Of Acoustic Emission For Early Crack Detection In Welded Steel Structures
Özlem Karabiber Cura Mehmet Göktuğ Efgan	*Izmir Katip Celebi University*	Development Of A Deep Learning Model To Identify Tibia Plateau Fractures On X-Ray Images
Özlem Karabiber Cura	*Izmir Katip Celebi University*	Schizophrenia Detection From Eeg: A Deep Learning And Brain Connectivity Approach

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SESSION-2, HALL-2 / OTURUM-2, SALON-2

MODERATOR: Muhammed Tatar

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Amjad Ali Muhammed Tatar	*Sivas University Of Science And Technology*	Crispr-Based Genome Editing Strategies For Sustainable And Precise Control Of Fungal, Bacterial, Viral, And Nematode Plant Pathogens
Muhammed Tatar Amjad Ali	*Sivas University Of Science And Technology*	Biogenic Nanoparticles For Sustainable Enhancement Of Plant Growth: Mechanisms, Applications, And Future Prospects
Behcet Pusmak Hakkı Dereli	*Izmir Katip Çelebi University*	Determination Of Fishing Effort And Catch Per Unit Effort (Cpue) Based On Fishing Gear In Demirköprü Dam Lake Fishery
Zehra Bozkurt Taha Elçarpar	*Afyon Kocatepe University*	Assessment Of Leg Health And Locomotor Function In Broiler Chickens
Zehra Bozkurt Mehmet Furkan Doğan	*Afyon Kocatepe University*	The Effects Of Catching Methods On Broiler Welfare And Carcass Quality
Nesrin Çakıcı Aslı Çerezoğlu	*Çanakkale Onsekiz Mart University*	The Hazard Of Salmonella Spp. And Shiga Toxin–Producing Escherichia Coli (Stec) In Raw Beef Samples
Nesrin Çakıcı Saliha Aydın	*Çanakkale Onsekiz Mart University*	Investigation Of The Risk Of Shiga Toxin–Producing Escherichia Coli (Stec) In Retail Cheeses Purpose
Menekşe Taş Divrik	*Sivas Cumhuriyet University*	Heavy Metal Pollution In Freshwater Ecosystems And Its Ecotoxicological Effects

27.11.2025
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SESSION-2, HALL-3 / OTURUM-2, SALON-3

MODERATOR: Etibar Vazirov

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Etibar Vazirov Mirmatin Seyidali	*Polytechnic University Of Turin*	Real-Time Air Quality Prediction For Azerbaijan Using Machine Learning And Open Atmospheric Data
Ahmed T. Kasim Abubakar D. Isah	*Federal University Of Technology Minna*	Integration Of Restorative Design Features In Resort Architecture In Abuja, Nigeria
Keerthana V Meenatchi S Kishore R Vaishnavi K Saravanan R	*Bharath Institute Of Higher Education And Research*	Telepharmacy And Digital Health Economics
Sobia Liaqat Anam Khan Umm Eman Syed Neelam Bibi Saba Ghayas Anam Yousaf	*Rawalpindi Women University*	Moderating Role Of Self-Concept Clarity Between Celebrity Worship And Desire For Fame Among Young Adults
Alok Kumar Shrivastav Sibam Indra Suparna Pal Basudeb Dey	*Jis College Of Engineering India*	Optimization-Based Decentralized Energy Management For Islanded Multi-Microgrid Systems With Renewable Integration
G. Nixon Samuel Vijayakumar Aishwarya. S Reshma. N Tharunikaa. P Tarnekaa. M Nivethitha. S.K Samiksha. R.K	*R .M .K. Engineering College*	Review On Planck's Quantum Theory
Farhan Rafiq Abu Bokkar Siddique	*Shahjalal University Of Science And Technology*	Spatial And Temporal Dynamics Of Par, Kd_490, And Sst In The Bangladesh Eez From 2016 To 2022
Rubaiatul Islam Zerin Kamrul Hossain Anisul Kabir Iffat Ara	*Islamic University*	Evaluating Public Health Risks Associated With Airborne Particulate Matter: A Gaussian Dispersion Modeling Of Rice Mills Emissions In Rural Bangladesh
Wafa Difallah Asma Difallah	*Tahri Mohammed University Of Bechar*	Ai And Iot Based Irrigation Management System

27.11.2025
Kyrenia Local Time: 11:30-13:30
Ankara Local Time: 12:30-14:30

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SESSION-2, HALL-4 / OTURUM-2, SALON-4

MODERATOR: Saira Malik

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Bakhtawar Fakhar Umm Eman Syed	*Rawalpindi Women University*	Role Of Empathy In The Relationship Between Pets Attachment And Mental Health Among Pet Owners
Shafiqul Islam	*University Of Rajshahi*	Multi-Omics Profiling Unveils Ube2c, Mcm2, Aurka, And Tp53 As Core Regulatory Hubs Of Interconnected Oncogenic Networks In Women's Breast, Ovarian, And Endometrial Cancers
Rabia Hameed Maryam Javed Aisha Zubair	*Rawalpindi Women University*	Silent Slights, Big Decisions: The Mediating Role Of Sense Of Agency In The Impact Of Gendered Microaggressions On Turnover Intentions Among Working Women
Saira Malik	*University Of Education*	Morpho-Anatomical, Physiological And Biochemical Responses Of Wheat (Triticum Aestivum L.) Varieties To Drought Stress, Rewatering, And Exogenously Application Of Copper Oxide Nanoparticles
Soufiane Ziani Driss Khattach Jamila Abderbi Zahra Zerrouqi	*Mohammed 1st University*	Geostatistical algorithms for evaluating groundwater quality in irrigation practices: A case study of the Guenfouda region, NE Morocco
Abderrahim Asbbane Otmane Hallouch Samira Oubannin Moussa Nid Ahmed Saïd Gharby	*Ibn Zohr University*	Valorization of Argan Tree: Influence of Origin, Morphology, Extraction, and Processing on the Chemical Composition and Quality of Its Various Parts
Mohammed Arifur Rahman Mojumder Sourav Hossain	*Ahsanullah University of Science and Technology*	Impact Of Rainfall Variability On Groundwater Recharge In Northwestern Bangladesh: A Case Study Of Rajshahi, Chapainawabganj And Noagaon
Olufunto Omodele Adeleye Esther Opeyemi Aworeni Gladys Deborah Olorunlowu Oluwatunmise Timothy Ajao Blessing Oluwatimilehin Ayandokun Oluwadara Ope Oluwasegun Yasar Olalekan Sulaiman Emmanuel Oluwagbenga Adejobi	*Ladoke Akintola University of Technology*	Ameliorative Role Of Syzygium Aromaticum On Behavioral Deficits, Oxidative Stress And Neuronal Apoptosis In Lead-Iron Co Exposure Induced Neurotoxicity In Harwich Strain Of Drosophila Melanogaster

27.11.2025
Kyrenia Local Time: 11:30-13:30
Ankara Local Time: 12:30-14:30

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SESSION-2, HALL-5 / OTURUM-2, SALON-5

MODERATOR: Minhajul Abedin

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Al Mahmud Suruj Qiu Xiaoping Jannatul Ferdosy Shimul Mahmud Khatami	*Harbin Institute of Technology*	Backdoor Security For Llm-Based Cybersecurity Systems: Beyond Jailbreaking To Persistent Threats
Endalamaw Yihune Amare Bitew Mekonnen Getahun Yemata	*Bahir Dar University*	Ethiopian Medicinal Plants, Phytochemical And Antioxidants: Systematic Review
Karunesh Tiwari Yosief Kasshun Hailu Danait Tesfamichael Keleta Delinael Kifleyesus Andemariam Lulia Yohannes Tesfay	*Mai-Nefhi College Of Science*	Investigation Of Saltwater Batteries As An Alternative Energy Storage Solution In Eritrea
Komal Pervaz Anam Khan Umme Eman Syed Neelam Bibi Adnan Adil Saba Ghayas	*Rawalpindi Women University*	Mediating Role Of Digital Identity Between Social Media Addiction And Self-Esteem
Alif Ali Jony Najmin Tamanna Bonna	*Sylhet Agricultural University*	Supercritical Water Gasification and Oxidation for Waste Treatment: A Systematic Review of Feedstocks, Catalysts, and Scale-Up Strategies
Ayoub Boualli Oussama Taouala Abdoullah Bimoussa Yassine Laamari Youssef Ait Itto Hamid Morjani Aziz Auhmani	*Laboratory of Organic Synthesis and Physico-Molecular Chemistry*	Novel Oxazole-Based Totarol Derivatives: Design, Hemisynthesis, Characterization, and Anticancer Evaluation
Nihal Mesmoudi Noureddine Hammani Khawla Ammouch Samir Ibenmoussa Abdellah Moustaghfir Naoual Oukkache	*Laboratory of Venoms and Toxins, Pasteur Institute of Morocco*	Hemorrhagic Activity of Cerastes cerastes and Daboia mauritanica Venoms: Indicators of Viper Bite Severity in Morocco
Minhajul Abedin	*Noakhali Science and Technology University*	Exploring the Impact of the 3 Zero Movement in Bangladesh: A Pathway to Sustainable Development

27.11.2025
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SESSION-3, HALL-1 / OTURUM-3, SALON-1

MODERATOR: Sevgi Ayhan

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Hatice Çörten Uğur Özcan	*Gazi University*	Sentiment Analysis And Rating Prediction In E-Commerce Furniture Reviews
Nazima Sadykova Nasır Narlıoğlu	*Izmir Kâtip Çelebi University*	Barriers And Opportunities For Ecotourism Potential In Kazakhstan: The Case Of Katon-Karagay National Park
Sevgi Ayhan Tutku Kılınç Erarslan	*Erciyes University*	Assessing The Sustainability Performance Of Airline Companies Through The Merec-Based Mabac And Marcos Methods
Assemgul Ualiyeva Nasır Narlioğlu	*Izmir Kâtip Çelebi University*	Ecotourism In The Steppes Of Kazakhstan: A Case Study Of Burabay National Park
Özge Büyükdeveci Adil Baykasoğlu	*Dokuz Eylül University*	Parallel Single Seekers Society Algorithm Incorporated Machine Learning For Solving Continuous Optimization Problems
Hilal Dursun Nihan Çetin Demirel	*Yıldız Technical University*	Position-Based Criteria Prioritization Using The Ahp Method And Their Alignment With Belbin Team Roles: An Automotive Industry Application
Resul Harman Yılmaz Delice	*Kayseri University*	Hierarchical Clustering Analysis And Disaster Risk Assessment Of Hazardous Material Storage And Facilities In Istanbul Districts
Ibrahim Besen Eren Coşkun Mahmut Berkan Alisinoğlu Burak Korkut Metin Bilgin	*Iletişim Bilgisayar Yazılım A.Ş.*	Development Of A Data-Security-Oriented, Agent-Based Intelligent Assistant For Metal Cutting Machines
Eren Coşkun Ibrahim Besen	*Iletişim Bilgisayar Yazılım A.Ş.*	Managesql: Dynamic Sql Query Generation And Database Performance Monitoring In Mes Systems Using Local Large Language Models

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SESSION-3, HALL-2 / OTURUM-3, SALON-2

MODERATOR: Düriye Korkmaz Düzgün

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Nail Mammadov Davud Tarverdili Gulshan Umud Mammmadova	*Azerbaijan State Economy University*	Adaptive Boundary Penalization And Error Analysis In Physics-Informed Neural Networks
Nurcan Gücüyenen Kaymak	*Doğuş University*	Bessel Polynomial Method For Fractional Differential Equations
Düriye Korkmaz Düzgün	*Ankara Hacı Bayram Veli University*	Jacobsthal And Jacobsthal-Lucas Differential equations
Mariam Aden Abdi Peri Güneş	*Gelisim Istanbul University*	Infrared-Based Defect Detection In Solar Panels Using Cnns
Ismet Alagöz Oğuz Taşdemir	*Kırşehir Ahi Evran University*	Short-Term Power Production Forecasting Using The Xgboost Algorithm Developed For Solar Power Plants
Tolga Kahve Aliihsan Koca	*Istanbul Technical University*	Numerical Study Of Helicopter Ditching And Capsize Behavior On Wavy Water
Furkan Kesim Aliihsan Koca	*Istanbul Technical University*	Numerical Validation Of Wall Condensation Phenomenon And Numerical Analysis Of The Helicopter Demisting Performance
Hale Günaçtı	*Sivas Science And Technology University*	Determination Of Potato Late Blight Disease Management Strategies In Çukurova Region Conditions
Hale Günaçtı	*Sivas Science And Technology University*	Fungal Diseases Of Potato (Solanum Tuberosum L.) And Integrated Disease Management Approaches

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Kyrenia Local Time: 14:00-16:00
Ankara Local Time: 15:00-17:00

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SESSION-3, HALL-3 / OTURUM-3, SALON-3

MODERATOR: Arjeta Xheka

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Marina Todor Stojanova Dragutin Djukic Monika Stojanova	*University Of Ss.*	Effect Of Calcium-Based Soil And Foliar Amendments On The Chemical Composition Of 'Cardinal' Grapevine Leaves, Shoots, And Berries
Soukaina Ameur Ahmed Bendaoud Abdellah Zeroual	*ChouaïbDoukkali University*	Theoretical Investigation of the Regioselective Cycloaddition of [e]-Fused 4- Acyl-1H-pyrrole-2,3-diones with Cyanamides: Electronic Structure Insights, Organic Photonic Properties, ADME/Toxicity Evaluation, and Molecular Docking Analysis
Ameilia Zuliyanti Siregar Indra Rahmadi Siti Julianita Siregar	*University Of Sumatera Utara*	Application Of Variance Of Refugia To Control Rice Stem Borer (Scirpophaga Innotata) In Rice Field Plantation In Northern Sumatera, Indonesia
Sumayya Akram Matloob Ahmad Sana Aslam	*Government College University Faisalabad*	Investigating Catalytic Pathways For N-Arylated Benzimidazole
Ibrahim Sani Dikko	*Umaru Musa Yar'adua University Katsina*	Crispr-Enhanced Engineering Of T Cells For Next-Generation Cancer Immunotherapy: A Molecular And Synthetic Biology Perspective
Mouhajar Siham Youssefı Abdelkader	*Hassan 1 University*	Data-Driven Predictive Maintenance In Industry 4.0: Evaluation Of Machine Learning Models On Synthetic Data
Ziaul Haider Chowdhury Mahfuj Ahmed Sizan Osman Gani Rasel	*Hajee Mohammad Danesh Science And Technology University*	High-Resolution Drought Hotspot Mapping Using Sentinel-Based Composite Indices
Amrouche Zoheir Mohammed Bouziane Djalal Laribi-Habchi Hassiba	*Djilali Bounaama University Of Khemis Miliana Algeria*	Microstructural, Microbiological &Amp; Physicochemical Quality Of Dairy Dessert Cream At Different Conservation Temperatures
Arjeta Xheka Klementina Puto Majlinda Çuedari	*University Of Tirana*	Influence Of Covid-19 Pandemic On Antibiotic Resistance Profiles Of Proteus Mirabilis In Urinary Tract Infections: A Retrospective Analysis

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SESSION-3, HALL-4 / OTURUM-3, SALON-4

MODERATOR: Derra Mourad

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Adel Deliou Takieddine Bouklia Samir Djimli Mohamed Kemiha Meriem Dehbi Sofiane Boulkroune Abdelkader Fidjah	*University Of Umsb Of Jijel*	Mechanical Behaviours Of Symmetric Unidirectionnal Composites Laminated E-Glass/Epoxy
Derra Mourad	*Ibn Zohr University*	Estimation Of The State Of Charge And Health Of A Lithium-Polymer Battery Using Ultrasonic Technology
Mahamudur Rahman	*Eco Design Consultants Bangladesh (Edcbd)*	Decarbonizing Our Environment: Advancing Sustainable Development Through Policies And Strategies
Saleh Ahmed Sohel Rana Maimuna Akter Koli	*Bangladesh Agricultural University*	Reducing Post-Harvest Losses: Botanical Control of Angoumois Grain Moth in Rice
Saida Es-Sanhajy	*Moulay Ismail University*	Investigation of the Thermoelectric Properties of Two-Dimensional Janus Materials
Y. Navyasree S. Sharada	*Jntua College Of Engineering*	Extraction Of Pectin Biopolymer From Jackfruit Peel: A Review
A. H. Dadum S.O. Ayo-Odifiri W. G. Brisibe A. Ebekozien C. Aigbavboa I.H. Dadum	*Gombe State University*	Feasibility of using rice straw bale as a walling material for sustainable and affordable low income mass housing in Gombe metropolis, Nigeria
A.H. Dadum U.M. Bashir A.K. Sarkile A.Y. Muhammad A.B. Shaba M. Chukwuma-Uchegbu S. Umar A.Y. Shinga A.I. Alkali G.H. Malachi	*Gombe State University*	Unmasking The Margins: A Bibliometric Analysis Of Geographical Bias In Afrocentric Architectural Research And Pathways To Pan-African Equity
Mohammed Denzira Ali Barhoumi Abdelmalek Matine El Mostafa Benharaf Brahim Lizoul Said Esskalli Zidane Zohra Abdessamad Tounsi Mohammed El Idrissi	*Sultan Moulay Slimane University*	Dft-Guided Analysis Of Regio- And Stereoselectivity In The Hydroboration-Oxidation Of A-Trans-Himachalene

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SESSION-3, HALL-5 / OTURUM-3, SALON-5

MODERATOR: Fatih Topaloğlu

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Atakan Sarioğlu Emre Isa Albak	*Bursa Uludağ University*	Analysis Of Static Balance Status In Commertial Tires
Fatih Özyurt Esra Yüzgeç Özdemir	*Fırat University*	Deep Learning-Based Detection and Tracking of Sunn Pest Damage on Wheat Grains Using YOLO and MOT
Fatih Özyurt Canan Koç Esra Yüzgeç Özdemir	*Fırat University*	Vitenet: A Novel Approach For Classifying Galaxy Morphology
Mustafa Kirtay Betül Uzbaş	*Konya Technical University*	Comparison Of Filter-Based Feature Selection Methods In Breast Cancer Diagnosis Using Machine Learning
Fatih Topaloğlu	*Malatya Turgut Ozal University*	Design Of An Artificial Neural Network-Based Decision Support System For Forensic Informatics Applications
Bahadır Bozkurt Tarık Talan	*Gaziantep Islam Science And Technology University*	Comparative Analysis Of Traditional Machine Learning And Deep Learning Models In Language Identification Problems
Ayşe Tekin Mehmet Kürşat Öksüz	*Erzincan Binali Yıldırım University*	Multimodal Emotion Analysis Based On Early Fusion Using Deep Learning Methods
Burak Kurşun Mehmet Arif Saltan	*Milli Savunma University*	Numerical Investigation Of The Effect Of Inside Pipe Geometry On Energy Storage Characteristics In Double Pipe Energy Storage With Phase Change Material (Pcm)

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SESSION-1, HALL-1 / OTURUM-1, SALON-1

MODERATOR: Sine Kaya

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Raziye Koçak Özden Salman	*Selçuk University*	Chemical Composition And Antimicrobial Potential Of Cupressus Species Essential Oils Against Plant Pathogens
Emine Kaya Altop Sine Kaya	*Ondokuz Mayıs University*	Weed Management In Regenerative And Organic Agriculture
Emine Kaya Altop Sine Kaya	*Ondokuz Mayıs University*	Integrated Policy Approaches For Sustainable Weed And Plant Disease Management
Yusuf Yerlikaya Nurinisa Esenbuğa	*Atatürk University*	Evaluation Of Socio-Demographic Characteristics And Feeding Practices Of Small Ruminant Farms In Erzurum Province
Nihat Atilla Nurinisa Esenbuğa	*Atatürk University*	Current Status And Development Opportunities Of Dairy Cattle Enterprises In Kars Province
Achmad Haris Christine Wulandari Ariyadi Agustiono Slamet Budi Yuwono	*University Of Lampung*	The Role Of Upstream Community Knowledge In Supporting The Sustainability Of Water Ecosystem Service Conservation In The Way Sekampung Sub-Watershed
Niger Sultana Refath Islam K. M. Ariful Kabir	*Bangladesh University Of Engineering And Technology*	Exploring Cooperation In Asymmetric Dyadic Games Through Spatial Monte Carlo Simulations And Network Structures
Brahim Lejdel	*University Of El-Oued*	Optimizing Agricultural Sustainability Through Artificial Intelligence And Big Data
Borshon Karmoker Pranto Shovon Shaha Tanvir Ahmmed Sadiatul Keya Zakariya Alam Bappi Shahriar Mahmud Rimon Minhajul Abedin Nilufa Akhter Banu Rezuanul Islam Mohammad Abu Hena Mostofa Jamal	*Islamic University*	Microbial Fuel Cell-Driven Evaluation of Exoelectrogen from Municipal Wastewater for Electricity Generation and Bioremediation

28.11.2025
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SESSION-1, HALL-2 / OTURUM-1, SALON-2

MODERATOR: Mouhamad Souhaib Toulaimat

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Ibrahim Halil Deger	*Hasan Kalyoncu University*	Comparative Analysis Of Meteorological Drought By Drought Indices And Trend Techniques: The Case Of Izmir
Salah Hajismail Mouhamad Souhaib Toulaimat	*Ankara Yıldırım Beyazit University*	Transitional Shelter Strategies For Post-Conflict Syria: Toward A National Framework For Resettlement And Recovery
Yavuz Delice Izzet Onur Berber	*Yalova University*	Analysis Of Fire Safety In Metro Stations Using Pedestrian Simulation And Design Recommendations
Sadık Varolgüneş Abdulhalim Karaşin	*Bingöl University*	Comparative Analysis Of Rapid Assessment Approaches For Residential Buildings In Bingöl
Sadık Varolgüneş	*Bingöl University*	Pathology Of Non-Seismic Progressive Collapses In Turkiye: A Case Catalog Analysis (1983–2025)
Ahmet Fazıl Kara Muhammed Alperen Özdemir Ferit Çakir	*Gebze Technical University*	Determination Of Lime-Based Mortar Elastic Modulus After Elevated Temperature
Emel Zeray Öztürk Hilal Şimşek	*Konya Technical University*	Comparative Analysis Of Modern Satellite-Derived Gravity Models With The Egm2008 Reference Model
Gizem Gül Katırcıoğlu Ebru Kavak Akpınar	*Fırat University*	Experimental Investigation Of The Effect Of Contamination On Pv Panel Surface Performance

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SESSION-1, HALL-3 / OTURUM-1, SALON-3

MODERATOR: Muhammad Imran

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Saiful Islam	*Zhongyuan University Of Technology*	Sentiment Analysis Of Public Opinion Texts Based On Large Language Model
Mohammed Imam Tawseef Ahmad Ch.Sunil Kumar R.Kanimozhi	*Bharat Institute Of Engineering And Technology*	Video Analyzer
Samiul Bashir Pronab Kumar Paul A.N.M. Shihab Uddin Bipul Islam Firoz Ahmed M. Hasnat Kabir	*University Of Rajshahi*	Design Of A Broadband S-Band Microstrip Antenna With Modified Ground Geometry For Biosystems And Maritime Radar Applications
Md. Shakil Ar Salan Jahid Hasan Md. Mostafizur Rahman	*Rajshahi University Of Engineering & Technology (Ruet)*	Assessing Urban Carbon Sequestration Potential Using Gis And Remote Sensing: Evidence From Rajshahi City, Bangladesh
Mandadi Neeraj Reddy Tawseef Ahmad Ch.Sunil Kumar M.Suresh	*Bharat Institute Of Engineering And Technology*	Bug Whisperer-Error Emotion Mapping
Muhammad Imran	*Government College University*	Composition And Emerging Applications Of Zingiber Officinale Essential Oil
Mofassel Hossen Akash Ashraful Alam	*Noakhali Science And Technology University*	Microwave-Assisted Green Synthesis Of Zno Nanoparticles Using Litchi Chinensis Leaves Extract And Their Application In Photocatalytic Activity
Leila Kebal Abdelhak Rouibi Noureddine Djebli	*University Ahmed Zabana-Relizane*	The In-Vitro Evaluation Of The Anti-Inflammatory Activity Of Olea Europaea L. Leaves Extract

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SESSION-1, HALL-4 / OTURUM-1, SALON-4

MODERATOR: Brahim Lejdel

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Ghulam Hussain Jie Zhang Ghulam Qanmber Mengli Yu Yujun Li Fuguang Li Zuoren Yang	*State Key Laboratory of Cotton Bio-breeding and Integrated Utilization*	GhMYB44 Orchestrates a Multi-tiered Cascade to Regulate Secondary Cell Wall Biosynthesis in Cotton Fibers
Isah M. C. Hamzat A. Olatunde, A. A. Ndana, T. K. Abdulmalik R. H.	*Ibrahim Badamasi Babangida University Lapai*	Growth Assessment and Economic Indices of Clarias gariepinus cultured in a Clarias-Duckweed Aquaponics System
Yahaya A. G. Isah M. C. Salihu I. M.	*Ibrahim Badamasi Babangida University*	Bacteriological Assessment Of Moussa Stream In Bida, Niger State, Nigeria
Ekijere Nathan Monday David Ikwuoche John Ogunmola Adeniyi Oyewole	*Federal University Wukari*	Nonlinear Randomised Complete Block Design And Analysis Of Saponins Effect On Crude Oil Spill Remediation
Irfanul Haque	*Software Quality Assurance Engineer, Brac It*	Bridging Qa Gaps With Ai: A Study Of Predictive Accuracy And Test Automation Efficiency
Leila Azaryouh Amine Miftah Zineb Kassab Khalifa El Harfi Mounir El Achaby Adil Aboulkas	*Université Sultan Moulay Slimane*	Valorization Of Olive Mill Waste Into Activated Hydrochar: Advancing Circular Solutions For Water Purification
Rahimova Konul Elbrus	*Azerbaijan State University Of Economics*	Study Of The Formation Of Chemical Burn-On On Steel Castings And The Use Of Anti-Burn Coatings Based On Kaolinite $Al_2Si_2O_5(Oh)_4$

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SESSION-1, HALL-5 / OTURUM-1, SALON-5

MODERATOR: Cherif Lamia

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Nur Mohamad Tanvir Hossain Bhuiyan	*University Of Rajshahi*	Ai-Powered Early Warning Systems For Infectious Disease Outbreaks: A Mini Review
Akhellouf Fatima Zahra Azzouzi Maryame Boukate Khadija Adlaoui El Bachir Amarir Fatima	*Hassan Ii University*	Phytochemical Screening And Evaluation Of The Antioxidant Activity Of The Hydroethanolic Extract Of Moroccan Myrtus Communis L.
S.Lakshmi	*Srm Institute Of Science And Technology*	A Study On Background Noise Removal Using Deep Learning Algorithms
Cherif Lamia Mahroug Hanane	*University Centre Of Maghnia*	Study Of The Physico-Chemical And Bacteriological Quality Of Groundwater: Case Of The Ghazaouet Region (Tlemcen Province)
Abdullahi Gabi Muhammad Alhassan Gabi Usman Adisa Moahmmed Jimoh Ibrahim Baba Usman Mohammed Chado Isah	*Ibrahim Badamasi Babangida University*	Proximate Analysis Of Peanut Products From Composite Flour Of Wheat, Groundnut, And Egg Formulated For A Moderate Person
Mahmuda Begum Kazi Md. Shihabul Islam Munna Miah Nusrat Nawrin Srabony Romel Ahmed Mohammad Masum Ul Haque Ajit Ghosh	*Shahjalal University Of Science And Technology*	Characterization Of Salt-Tolerant Bacillus Spp. As Plant-Growth Promoting Endophytic Bacteria Enhancing Tomato Seedling Growth Under Salinity Stress
Le Tran Thanh Liem Tran Thi Kim Hong Bui Thi Bich Lien	*Can Tho University*	Beyond Species: An Integrated Approach To Biological Resource Management In Biodiversity Hotspots

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SESSION-1, HALL-6 / OTURUM-1, SALON-6

MODERATOR: Belhadj Tahar Kamel

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Belhadj Tahar Kamel Adjoudj Abdellatif Benmeddah Mohammed Missoum	*University Morsli Abdellah Of Tipaz*	Assessing The Impact Of Agricultural Activity On The Biodiversity Of Mount Chenoua In Tipaza Region North Of Algeria
Imane Mouamr Karim Chkirate Mohammed. Benmessaoud	*Mohammed V University In Rabat*	Electrochemical, Structural And Thermodynamic Investigations Of Cannabis Seeds Oil (Cannabis Sativa L) As A Green Corrosion Inhibitor For C38 Steel In Hcl
Amine El Maraghi Habib El Alaoui El Abdallaoui Hocine Garmes Abdellah Zeroual	*Chouaïb Doukkali University*	Corrosion Inhibition Of Steel By 2-Ethyl-6-Nitro-2h-Indazole (6ne2): Experimental And Theoretical Insights Into Adsorption And Mechanistic Behavior
Alarima, I. M. Okparavero, O.O. Oyekale, J.I.	*School Of Agriculture, Federal Polytechnic Ilaro, Ogun State, Nigeria*	Economic Assessment Of Neem Organic Fertilizer Application On Cucumber (Cucumis Sativus L.) Production In The Rain Forest Ecological Zone
Radouane El Amri Rajaa Zahnoune Otmane Boudouch Cherki Lahlou Aziz Hasib Noureddine Kamil Reda Elkacmi	*University Sultan Moulay Slimane*	Sustainable Optimization Of Reverse Osmosis Pretreatment Of Brackish Water Using Coagulation-Flocculation And Sludge Recirculation: A Box- Behnken Approach
Zakaria Asbai Souhaila Elhairech Bouchaib Bahlaouan Said El Antri Nadia Boutaleb	*[1]Hassan Ii University Of Casablanca*	Eco-Engineering Of Omfs: Reducing Environmental Footprint Through Advanced Formulation And Release-Control Processes
Amroumoussa Benmoussa Mohammed Hssaisoune Lhoussaine Bouchaou	*University Ibn Zohr*	Assessment Of The Impact Of Lithological And Topographical Variability On Soil Mechanics And Environmental Sustainability In Jorf Lasfar, Focusing On The Dynamics Of Karst Aquifers

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SESSION-2, HALL-1 / OTURUM-2, SALON-1

MODERATOR: Simge Güneşer

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Meltem Ince Yenilmez	*Izmir Democracy University*	Achieving Gender Equality In Engineering: Barriers, Impacts, And Solution-Focused Strategies
Hilal Abat Huriye Sebnem Burnaz	*Istanbul Technical University*	Factors Affecting Consumers' Purchase Intention Toward Green Personal Care Products
Pınar Şaşmaz Kavas Simge Güneşer Kholoud Saleh	*Girne American Univercity*	A New Paradigm In Digital Preservation Of Historic Structures: Ai-Based Documentation, Cultural Communication, And Sustainable Tourism Branding
Pınar Şaşmaz Kavas Simge Güneşer Kholoud Saleh	*Girne American Univercity*	A Multidisciplinary Approach To Protecting At-Risk Historic Structures: Data Analytics, Public Communication, And Conservation Economics
Emre Can Değiş Kayhan Ayar	*Sakarya University*	The Role Of Virtual Reality (Vr) Simulations In Industry 4.0 Education
Bahu Sönmez Tülay Boyraz Şerife Ünal Tolga Karaköy	*Sivas University Of Science And Technology*	Sustainable Agricultural Systems In Environmental, Economic, And Social Dimensions
Orhan Atakan Gürbüz Gülden Gök Oya Özel Gürbüz	*Niğde Ömer Halisdemir University*	Hospital Waste In The Context Of Environmental Sustainability
Nesrin Dursun	*Ardahan University*	Types Of Drought, Causes And Effects

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SESSION-2, HALL-2 / OTURUM-2, SALON-2

MODERATOR: Elif Şahin Suci

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Sena Erdinç Akoğul Kadriye Oktor	*Kocaeli University*	Evaluation Of Microalgae Harvesting Methods With Multi-Criteria Decision-Making Mechanisms: A Topsis Example
Gazel Burcu Aydın	*Trakya University*	Evaluation Of Maksutlu Dam Lake (Sivas, Türkiye) Water Quality In Terms Of Elemental Load
Kemal Aydın Dağ Tülay Kaplan Fatma Eda Tutar	*Sivas University Of Science And Technology*	Impact Of Digital Farming On Farmer Behavior And Agricultural Policies
Elif Şahin Suci	*Selçuk University*	Dairy Cattle In The Climate Change Era: Precision Livestock Farming And Digital Sensor Approaches
Emine Betül Keleş Elif Şahin Suci	*Selçuk University*	The Role Of Storage Infrastructure In Strategic Agricultural Commodities: The Structure Of Grain Production And Licensed Warehousing In Türkiye
Yasemin Durgut Serpil Kiliç Depren	*Yıldız Technical University*	A Study On The Actuarial Climate Index For Istanbul
Begüm Nisa Tosun Hakan Demiral	*Eskişehir Osmangazi University*	Synthesis Of Metal Boride Catalysts And Their Hydrogen Production Applications

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SESSION-2, HALL-3 / OTURUM-2, SALON-3

MODERATOR: Hale Günaçtı

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Birsen Açıkel	*Eskisehir Technical University*	Regulation, Safety And Certification Issues In Autonomous Flights
Ahmet Eşiyok	*Istanbul Beykent University*	Occupational Health And Safety In Rapid Prototyping Processes Using The Stereolithography (Sla) Method
Alperay Altıkat	*Iğdır University*	Light And Energy Management In Controlled/ Vertical Plant Production: Artificial Intelligence–Based Optimization Strategies
Alperay Altıkat	*Iğdır University*	Life Cycle Assessment And Emission–Energy Optimization In Agricultural Biomass Pellet Fuels
Erkan Öztürk Hüseyin Yıldız	*Istanbul University-Cerrahpaşa*	Computer-Aided Simulation Of A Small-Scale, Single-Joint Magnetic Inverted Pendulum Mechanism
Cuneyt Genyüz Mustafa Korkmaz Ruya Samli Eylem Yucel Demirel	*İstanbul University*	Digital Transformation In Logistics: Automation Of Delivery Verification Processes Through The Pod Tracking System
Enes Uğur Ethem Kelekçi	*Manisa Celal Bayar University*	A Python Based Framework For Kinematic And Dynamic Analysis And Simulation Of Industrial Robotic Arms
Hale Günaçtı	*Sivas Science And Technology University*	Assessment Of Sugar Beet Significance And Plant Protection Challenges In Sivas Province
Hale Günaçtı	*Sivas Science And Technology University*	Blueberry (Vaccinium Corymbosum): Studies In Turkey And Worldwide, Pre- And Post-Harvest Diseases And Control Methods

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SESSION-2, HALL-4 / OTURUM-2, SALON-4

MODERATOR: Melik Sami

Meeting ID: 929 9691 8209
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AUTHOR	AFFILITION	ABSTRACT TITLE
Najia Tahsin Kumkum Sheikh Jakia Nur Oishee Monjurul Rana Abdul Awal Delwar Hossain A. J. Saleh Ahammad	*Jagannath University*	Fabrication Of Co(Ll)-Fe(Ll)-Ni(Ll)-Based Heterometallo Supramolecular Polymer For Electrochemical Sensing Of 4-Nitrophenol
Al-Rafi Chowdhury Mahi Abdullah Al Azad Al-Imran Sajnin Sampa Asif Ali Shishir	*National University Bangladesh*	Real -Time Heartbeat, Ecg, Spo_2 And Temperature Monitoring Using A Smart Iot Device
T .Venkatesh S. Sharada	*Jntua College Of Engineering*	Advances In Eco-Friendly Anticorrosion Coatings: Recycled Polypropylene And Zno Nanoparticles For Aluminium Alloys-Review
Brahim Lizoul Said Es-Sakali Mohammed Denzira Ali Sbai Mounia Achak Said Kounbach	*Hassan First University*	Use Of Amorphous And Apatitic Tricalcium Phosphate To Remove Ni 2+ , Co 2+ And Cu 2+ From Aqueous Solutions
S. Lakshmi	*Srm Institute Of Science And Technology*	Towards A Sustainable Agricultural Revolution With Cognitive Systems
Melik Sami Khelil Sara Tallal Abdel Karim Bouzir	*Mohamed Khider Biskra University*	Cross Ventilation In Desert Homes: Spatial Strategies For Passive Cooling In Biskra.
Melik Sami Khelil Sara Tallal Abdel Karim Bouzir	*Mohamed Khider Biskra University*	Skyscrapers Of Sustenance: Integrating Vertical Farming Into Urban Architectural Systems
Osman Gani Rasel Ziaul Haider Chowdhury Mahfuj Ahmed Sizan	*Hajee Mohammad Danesh Science And Technology University*	Seasonal Assessment Of Pm2.5 In Cumilla District, Bangladesh Using Modis-Derived Ghap Data And Google Earth Engine
Mahfuj Ahmed Sizan Osman Gani Rasel Ziaul Haider Chowdhury	*Hajee Mohammad Danesh Science And Technology University*	Spatio-Temporal Dynamics Of Urban Expansion In A Northern District Of Bangladesh Using Viirs Night-Time Lights And Modis Land Cover In Google Earth Engine

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SESSION-2, HALL-5 / OTURUM-2, SALON-5

MODERATOR: Rozina Khattak

Meeting ID: 929 9691 8209
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AUTHOR	AFFILITION	ABSTRACT TITLE
Vaishnavi.K R.Kishore R.Sriarasuvasan S.Rubinthara R.Devi A. Palaniswamy R.Srinivasan	*Bharath Institute Of Higher Education And Research, Chennai*	Gold Nanoparticles: Preparation, Properties, And Applications In Bionanotechnology
R . Kishore K . Vaishnavi S . Meenatchi V . Keerthana	*Bharath Institute Of Higher Education And Research Chennai*	Plastic Pollution And Biodegradation Strategies
Abhigyan Ganguly Kumarjit Singha Bijoy Debnath	*Brainware University*	Cancer Cell Detection Using Machine Learning: A Comparative Study Of Knn, Svm, And Random Forest
Rozina Khattak	*Shaheed Benazir Bhutto Women University*	Synergistic Activation Of Solar Photocatalysis And Oxidants For Rapid Detoxification Of Industrial Effluents
Rozina Khattak	*Shaheed Benazir Bhutto Women University*	Harnessing Fruit And Nut Waste For The Efficient Biosorption Of Industrial Dye Pollutants
Amine Sarhrani Mohamed Sadiki Brahim Jaafar Yousra Hamoumi Nouhaila Lassfar Abdelhak Bouabdli	*Ibn Tofail University*	Assessing Anthropogenic Impacts On The Kenitra Coastal Dune Cordon (1999–2025): A Remote Sensing And Gis Study
Alip Kumar Paul, Mim Huda Umma Nourin Sawon Hasibul Islam Mohammad Nyme Uddin Hasan	*Building Energy &Amp; Environmental Management-Beem Enhanced By Ai*	Floor-Level Prediction In Multi-Storey Mosques Using Interpretable Machine Learning: A Case Study From Dhaka, Bangladesh
Aneta Nycz Janusz Skrzypacz Przemysław Szulc	*Wroclaw University Of Science And Technology*	Comparative Analysis Of Flow Through Various Gap-Blade Configurations In A Low-Specific-Speed Centrifugal Pump
Ritu Mondal Diganta Bose Moznuzzaman	*Jashore University Of Science And Technology*	Foot Movements Classification By Machine Learning Algorithm With Optimized Electromyography Features

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SESSION-2, HALL-6 / OTURUM-2, SALON-6

MODERATOR: Fedwa Beghdadi

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Fedwa Beghdadi El-Hadj Driche	*Hassiba Benbouali University Of Chlef*	Isolation Of Saharan Actinobacteria For Biological Control Against Phytopathogens: Towards Sustainable Agriculture
Fedwa Beghdadi El-Hadj Driche	*Hassiba Benbouali University Of Chlef*	Environmental And Consumer Health Risks Associated With Mycotoxins Produced By Phytopathogenic Fungi
Araftuzzaman Bhowmik Shimu Khairul Islam Rokibul Islam	*University Of Rajshahi*	Effect Of Different Levels Of Phosphorus And Boron On Growth And Yield Of Two Potato Varieties (Solanum Tuberosum L.)
Yeamin Hossain Ridwanul Islam Mahfuj Ahmed Shohag Rana Nishat Tasnim Ananty Sufara Akhter Banu Abu Yousuf Hossin Golam Robbani Shahanaz Parveen Kazi Kamrul Huda Harun-Ur-Rashid	*Sher-E-Bangla Agricultural University*	Genome-Wide Meta-Qtl Analysis Uncovers Stable Loci Underlying Fruit Traits, Plant Morphology, Anthocyanin Regulation, And Biotic Stress Resistance In Eggplant
B. Sri Chetan Tawseef Ahmad M.Suresh Ch.Sunil Kumar	*Bharat Institute Of Engineering And Technology*	Reversible Data Hiding In Encrypted Images
Bijender Singh Sumit Kumar Davender Singh	*Central University Of Hartana*	Microparticles-Assisted Engineering Of Fungal Morphology For Enhanced Production Of Hydrolytic Enzymes
Md Shahinur Islam Bishwo Mainali Mary Whitehouse	*Macquarie University*	Biological Control Potential Of Green Lacewings And Comb-Footed Spider On Fall Armyworm (Spodoptera Frugiperda) And Screening Natural Enemies Of Fall Armyworm By Using Molecular Gut Content Analysis

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SESSION-3, HALL-1 / OTURUM-3, SALON-1

MODERATOR: İlhan Danacı

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Ilayda Aydınlı Muhammed Semih Dihye Baş Ilhan Danacı Fuat Erden	*Sivas University Of Science And Technology*	Self-Healing Materials For Autonomous Maintenance And Repair In Aerospace
Ilhan Danacı Fuat Erden	*Sivas University Of Science And Technology*	Optimization Of Thermoelectric Properties In A-Swnt/ Poly(Aniline-Co-Acrylonitrile) Composites Via Controlled M-Cresol Re-Doping
Adnan Baday Onur Duman	*Berdan Cıvata Ar-Ge Merkezi*	Lining Improvement Project In Hot Bolt Forging Fraction Presses
Emre Erdem Alper Çalışkan	*Yıldız Technical University*	Enhancement Of Isolation In 5g 1×2 Mimo Patch Antennas By Employing Defected Ground Structure (Dgs)
Gizem Candaş Berkay Menç Yusuf Özçatalbaş	*Gazi University*	Mechanical Behavior Of The Interface In The Industrial Joining Of Cfrp–Metal Hybrid Structures
Berkay Menç Yusuf Özçatalbaş	*Gazi University*	Fabrication Of Open-Cell Alumina Ceramic Foams Via The Replica Method
Ömer Saltuk Bölükbaşı Efe Arıyol	*Iskenderun Technical University*	Investigation Of Relationships Of Lsi Index With Mild Steel Corrosion Coupons
Ömer Saltuk Bölükbaşı	*Iskenderun Technical University*	Chemical Risk Factors In The Iron And Steel Industry
Serkan Islak	*Kastamonu University*	Microstructure, Density And Hardness Evolution Of Mo-Sm 2 O 3 Composites
Serkan Islak	*Kastamonu University*	Development Of Copper-Matrix Composites: A Literature Review

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SESSION-3, HALL-2 / OTURUM-3, SALON-2

MODERATOR: Aylin Er

Meeting ID: 929 9691 8209
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AUTHOR	AFFILITION	ABSTRACT TITLE
Buse Atalay Aylin Er Pınar Güner	*Balıkesir University*	Antimicrobial Peptides: Structural Diversity, Mechanisms, And Clinical Perspectives
Selin Meryem Şengül Aylin Er Pınar Güner	*Balıkesir University*	Role Of Boron And Boron Compounds In Crop Production And Insect Pest Management
Mehmet Akif Kalender	*Selçuk University*	Assessment Of Agricultural Water Use In Arid Regions: A Case Study Of Konya - Karapinar District
Mustafa Çomaklı Bahadır Sayinci	*Atatürk University*	Numerical Analysis Of Internal Flow Characteristics In Hollow Cone Nozzle Plates Used In Pesticide Applications
Ipek Zeynep Durusu Aliye Ezgi Güleç Taşkıran	*Başkent University*	Comparative Antioxidant Profiling Of 18 Pharma-Grade Cosmeceutical Oils Using The Dpph Radical-Scavenging Assay
Haydar Küplemez Fatih Seyis	*Recep Tayyip Erdoğan University*	Secondary Volatile Metabolite Composition Of Helichrysum Pallasii Collected From Anzer/Rize
Haydar Küplemez Fatih Seyis	*Recep Tayyip Erdoğan University*	Secondary Volatile Metabolite Composition Of Hypericum Pruinatum Collected From Rize

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SESSION-3, HALL-3 / OTURUM-3, SALON-3

MODERATOR: Erdem Gülümser

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Rüstem Emre Sungurbaş	*Me-Ge Teknik A.Ş.*	Reduction Of Input Ripple Behavior In Full Bridge Inverters By Using Capacitors
Mohammed Ahmed Ali Ali Peri Güneş	*Gelisim Istanbul University*	Optimal Design Of Fuzzy Logic Controller For Automatic Voltage Regulator
Fatma Çalili Çankır	*Iskenderun Teknik University*	Prediction Of Effective Diffusivity In Nanocellulose-Based Sandwich-Type Membranes For Polymer Electrolyte Fuel Cells
Mohammed Wakas Saad Peri Güneş	*Gelisim Istanbul University*	Performance Evaluation Of Pid Vs. Fuzzy Logic Control For First-Order Water-Level And Thermal System
Emre Torun	*Sivas University Of Science And Technology*	Numerical Investigation Of The Effect Of Rt35hc Phase-Changing Material On Entropy Production In Battery Thermal Systems
Mert Avcı Arif Gülten	*Fırat University*	Pesoptimization Of Cnn Hyperparameters In Planus Diagnosis Using Meta-Intuitive Methods optimization
Feyza Deretaşi Erdem Gülümser	*Bilecik Şeyh Edebali University*	Phytotherapy In Animal Health And Nutrition: Phytotherapeutic Plants
Erdal Ibrik Erdem Gülümser	*Bilecik Şeyh Edebali University*	The Situation Of Rural Development Supports In Bilecik

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SESSION-3, HALL-4 / OTURUM-3, SALON-4

MODERATOR: Al Amin

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Al Amin	*International Islamic University Malaysia*	Performance Evaluation And Trade-Off Analysis Of Pam, Qam, And Cpm In High-Speed Lifi Communication
Hicham El-Boukhary Hamza Elkissany Adil Laaziz Abdelouahed Hajjaji	*Sultan Moulay Slimane University*	Endophytes And Nanoparticles Combination
Bibi Hafsa Mahib Reza S M Sabbir Hosen A S M Zinnurain Swadhin	*Jahangirnagar University*	Geospatial Approaches To Environmental Monitoring And Risk Zonation Of Mahasthan Archaeological Heritage Site Of Bangladesh
Abah Roseline Toyin Agbo Christiana Ene	*University Of Abuja,*	A Compartmental Mathematical Model For Understanding Heart Disease Dynamics And Prevention
Tharunikaa P Vanthana G Arsa G M Varshana Deepa A. Vijayalakshmi	*R.M.K. Engineering College*	Smart Wearables For Health Monitoring Using Nanotechnology
Barani Chandran S Jeyanth R T Karan Logeswaran P Lokeshkumar K A. Vijayalakshmi	*R.M.K. Engineering College*	Microplastic Pollution In Freshwater Ecosystems
Khadija Akter Akhi Apurbo Kumar Biswas Rahima Nasrin	*University Of Barishal,*	Investigation Of Structural And Optical Characteristics Of Undoped And Ni-Doped Cuo Thin Films Synthesized Via Cbd
Barani Ethirajan G Priya Murugesan Kamaraj	*Srm Institute Of Science And Technology, Ramapuram Campus, Chennai*	Decoding Pollutant Toxicity Using Crispr/Cas9 For Applications In Modern Ecotoxicology

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SESSION-3, HALL-5 / OTURUM-3, SALON-5

MODERATOR: Palash Kumar Das

Meeting ID: 929 9691 8209
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AUTHOR	AFFILITION	ABSTRACT TITLE
Md Partha Abu Shahed Abdul Halim Jahangir Alam	*Jashore University Of Science And Technology*	Evaluation Of Viscosity Of 1,1,1,2-Tetrafluoroethane (R134a) Using Green-Kubo Approach By Molecular Dynamics
Yash Ajay Gadale Mayur M. Maske	*K. E. Society's Rajarambapu Institute Of Technology, Rajaramnagar*	Advances In Concrete 3d Printing For Civil Engineering
Abderrahim Bahoum Mohamed El Hattab Youness El Hammami	*Ibn Zohr University*	Mixed Mhd Convection And Heat Transfer Enhancement In A Driven Cubic Cavity Using A Cu–Al_2O_3/Water Hybrid Nanofluid
Siham Kharraz Mohammed Nabil Kabbaj Mohammed Benbrahim	*Sidi Mohamed Ben Abdellah University*	A Hybrid Catboost-Based Spatiotemporal Fusion Model For Accurate Daily Land Surface Temperature Estimation Across African Climate Zones
Aditya Dev Mohammed Arifur Rahman Mojumder Rafiul Amin	*Ahsanullah University Of Science And Technology*	Assessing Groundwater Depletion In Bangladesh Using Grace Satellite Data: A Humanitarian Engineering Approach For Sustainable Water Management In Dhaka City
Palash Kumar Das	*Hajee Mohammad Danesh Science And Technology University*	An Application Of Mixed-Integer Linear Programming To Minimize The Cost Of University Students Required Basic Nutritional Requirements
Raduanul Haque Maruf Aaratrik Utsav Das Shahadat Hossain Mohammad Junaid Pabel Shahrear	*Shahjalal University Of Science And Technology*	Modeling Short-Range Artillery Trajectories With Progressive Drag And Wind Effects
Shahidul Islam	*Barishal Textile Engineering College*	Interpretable Machine Learning Framework Using Xgboost, Catboost, And Shap For Predicting Yarn Tensile Strength

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SESSION-3, HALL-6 / OTURUM-3, SALON-6

MODERATOR: Mahafuzur Rahman

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Chakroune Soukaina Maghnouj Abdelmajid El Mahjoub Chakir	*Sidi Mohamed Ben Abdellah University*	Neutronic Modeling Of A Nuscale-Type Smr With Openmc: Analysis Of K Eff And Burnup Behavior
El Handaoui El Mehdi Salim Ahmed Abderrahim Jrifi Omar Fanidi	*Ensam Hassan Ii University*	Adsorptive Removal Of Methylene Blue Onto Activated Carbon Prepared From Bamboo: A Study Of Kinetics And Isotherms
Tanvir Anjum	*University Of Dhaka*	Multifunctional Cu, B Co-Doped Zno Photocatalyst: Organic Pollutant Degradation And Antimicrobial Coatings
K.R.Padma K.R.Don	*Women's University*	Stress Tolerance And Plant Growth Promotion Through Seaweed Extract
Sabiha Nusrat Sajib Deb Helal Murshed Swarup Deb	*Texas Tech University*	Stimuli-Responsive Nanoparticle-Assisted Immunotherapy: A New Weapon Against Solid Tumours
Mahafuzur Rahman	*Begum Rokeya University*	Identifying Key Influencers Of Patient Satisfaction Using An Explainable Machine Learning Approach
Habibur Rahman Ekhtiar Uddin	*Southeast University*	The Convergence Of Bioinformatics And Omics Technologies In Biomedical Discovery
M. Alhassan Y. Ndatsu M. C. Isah I. A. Musa	*Ibrahim Badamasi Babangida University*	Growth Performance And Feed Efficiency Of Clarias Gariepinus Fed Graded Levels Of Sesame Indicum (Beni Seed) As Fish Meal Substitute
Anna Piwowar Przemysław Jaszak Marcin Bieganowski	*Wroclaw University Of Science And Technology*	Research On Structuring Of Sealing Surfaces

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SESSION-1, HALL-1 / OTURUM-1, SALON-1

MODERATOR: Kadriye Filiz Balbal

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Mehmet Şenel Kamil Özpınar	*KTO Karatay University*	Design And Analysis Of An Experimental Test Setup For Multi-Parameter Fluid Measurements
Melih Emre Karacaoğlu Nurullah Gültekin	*Idea Group Project Engineering Consultancy*	Investigation Of Gaseous Fuels Used As Secondary Fuel In Gasoline Gas Dual Fuel Spark-Ignition Engines
Yağmur Naz Değnekçi Anıl Geyik	*Cms Jant Ve Makine Sanayii A.Ş.*	Prevention Of Thermal Fatigue Cracks And Extending Mold Lifetime Through Improved Welding Procedures
Anıl Geyik Tarkan Alioğulları Ergin Uzun Yağmur Naz Değnekçi	*Cms Jant Ve Makine Sanayii A.Ş.*	Improving Production Efficiency Through Post-Processor Enhancements And Probe Integration In Cnc Machines
Alaaeddin Kheiti Kadriye Filiz Balbal	*Dokuz Eylul University*	The Impact Of Llm-Based Ai Agents: Experimental Comparison Between Single And Multi-Agent Ai Structures
Ilke Çiftçi Serap Çelen	*Ege University*	An Investigation On Micro Hardness And Production Times Of Aisi H13 Tool Steel Welding With Different Filler Wires
Zeynel Abidin Altunkaynak	*Koluman Otomotiv Endüstri A.Ş.*	Maintenance Levels And Training Dynamics In Military Vehicles: Analysis Of User, Unit, And Factory-Level Approaches
Hacer Çolak	*Kilis 7 Aralık University*	Evaluation Of Analytical And Numerical Approaches In Estimating The Fundamental Period Of Buildings

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SESSION-1, HALL-2 / OTURUM-1, SALON-2

MODERATOR: Sefa Altıkat

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Sinem Kılıçkap Işık Abdulkadir Çoşkun Adem Yar	*Bingöl University*	Enhancing Of Paraffin-Based Phase Change Materials With Next-Generation Nanomaterials
Gizem Durak Yüzüak Ercüment Yüzüak	*Munzur University*	Exploring Magnetic Properties Of $GdCO_2$ Thin Film
Ali Berk Tavacı Yusuf Özçatalbaş	*Gazi University*	The Mechanical Effects Of Laser Cutting On Armor Steels
Ahmet Erdem Haberdar Volkan Acar Ferit Çakır	*Gebze Technical University*	Non-Impregnation Problem In Frp Ropes
Necla Altın Sema Samatya Yılmaz Ayşe Aytaç	*Kocaeli Üniversitesi*	Production And Characterization Of Biodegradable Rgo/P3hb4hb Composite Membranes For Fuel Cell Applications
Saeid Darvishi Necla Altın Ayşe Aytaç	*Kocaeli Üniversitesi*	Investigation Of The Effects Of Zno Nanoparticles On The Structural, Thermal And Mechanical Properties Of Pla/Pbs Based Composites
Sefa Altıkat Recep Özcan Dündar	*Iğdır University*	Effects Of Electromagnetic And Magnetic Fields On Germination And Stress Physiology In Plant Biosystems
Recep Özcan Dündar Sefa Altıkat	*Iğdır University*	The Effect Of Physical-Mechanical Agricultural Production, Processing Technologies, And Quality Standards On Seeds

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SESSION-1, HALL-3 / OTURUM-1, SALON-3

MODERATOR: Demet Büyükkaya

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Alper Olcay Pinar Düzgün Süreyya Aydın Yüksel	*Yıldız Technical University*	Production And Characterization Of Silicon-Based Acetone Sensor Prepared Under Room Conditions
Lütfullah Taha Halıcı Seher Eken	*Istanbul Technical University*	A Computational Study Of Ballistic Response In Multi-Layer Textile Protection Systems
Demet Büyükkaya Hasan Şahin	*Bursa Teknik University 29 Una İstiyor*	Comparative Analysis Of Deep Learning Approaches In E-Commerce Delivery Time Prediction: An Application Of Mlp, Lstm, And Cnn Models
Demet Büyükkaya Hasan Şahin	*Bursa Teknik University*	Inventory Optimization Through K-Means Clustering For Data-Driven Decision Support
Ferhat Özdemir Burak Görgel	*Kahramanmaraş Sütçü Imam University*	Economic Assessment And Cost Analysis Of Engineered Wood Products
Ferhat Özdemir Burak Görgel	*Kahramanmaraş Sütçü Imam University*	Structural Characteristics And Construction Applications Of Engineered Wood Materials

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SESSION-1, HALL-4 / OTURUM-1, SALON-4

MODERATOR: Fatima Osmani

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Tebboune Wafa Hadjadj Fatima Zohra Belkheir Wissem Bounouara Zahra Bourada Fouad Ait Sidhoum Imène	*University Of Sciences And Technology Mohamed Boudiaf*	A Novel Trigonometric Shear Deformation Model For Predicting The Thermal Buckling Of Composite Structures
Yong Jin Muhammad Aslam Payam Shafigh	*Wenzhou University Of Technology*	A Review On Standard Design Parameters For Rammed Earth Wall Construction
Mohd. Jamshaiya Raza Riyazuddeen Chandra Mouli Pandey	*Sgt University*	Ionic-Liquid Grafted $Nife_2O_4$/G-C_3N_4 Nnaohybrid For Ultra-Sensitive And Selective Electrochemical Melamine Monitoring
Suleiman Zuleihat Ozohu Ado A. Datti Kazeem Ibraheem Ajadi Bakare Abdulakeem Oyesode Olotu Johu Abubakar Ahmed Aliyu Nana Aisha	*Ahmadu Bello University Zaria*	Utilizing Lowcost Eggshell And Coconut Mixtures As Efficient Adsorbents For Removing Lead And Chromium From Tannery Effluent
Dipok Halder Hasan Ali Sanjay Das Humaira Akter Shanta	*Bangladesh Agricultural University Mymensingh-2202*	Evaluating Water Hyacinth Residue As A Viable Alternative To Conventional Organic Fertilizer
Kater Titus A. J Simon D. O. Alonge	*Federal University Of Technology*	Enhancement Of Safety And Accessibility In The Design Of A Public Transportation Hub For Minna, Niger State
Melik Sami Khelil Sara Tallal Abdel Karim Bouzir	*Mohamed Khider Biskra University*	Seeing And Selling The City: Visual Consumption And The Erosion Of The 'Right To The City'
Fatima Osmani	*International Ahlulbait University*	Role Of Women In Sustainable Development: Challenges And Opportunities

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SESSION-1, HALL-5 / OTURUM-1, SALON-5

MODERATOR: Maria-Ioana Socaciu

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Rifat Uddin Nishat Farzana Tasnim Tinni Saha Kazi Samia Rashid Morshedul Kadir Masum Sadia Islam Swarna Sozon Ali Ashik Ali Abu Rihan Mizanur Rahman	*University Of Rajshahi*	Enhancing Productivity And Profitability In Onion Farming: Insights From Farmer Practices And Constraints In Bangladesh
Maria-Ioana Socaciu Maria Jenica Urs Melinda Fogarasi Vlad Mureșan Anda Elena Tanislav Adriana David Cristina Anamaria Semeniuc	*University Of Agricultural Sciences And Veterinary Medicine Cluj-Napoca*	Strategy For Sustainable Nutritional Fortification Of Summer Salami Via Oilseed Press Cakes
Aditya Dev Khadizatul Kobra Snahomoni	*National University*	Spatiotemporal Climate-Induced Migration Hotspots In South Asia: A Geospatial-Humanitarian Engineering Approach Using Satellite Remote Sensing And Socioeconomic Indicators In Bangladesh
Noman Habib Hafsa Shamsa Rana	*Government College University*	Physio – Biochemical Responses Of Wheat (Triticum Aestivum L.) To Exogenously Applied Hydrogen Peroxiode And Sucrose Under Salt Stress
Tsegmid Namsraijav Badamjargal Sodnom	*Mongolian University Of Life Sciences*	Observing Nesting Birds On The South Khangai Plateau In Spring
Shuvo Ronjon Das Moznuzzaman	*Jashore University Of Science And Technology*	Classification Of Multifidus Surface Electromyography For Low Back Pain Detection: Superior Performance With Frequency- Domain Features
Thumma Rushikesh Tawseef Ahmad Syeda Hafsa Naaz Juveria Nargis	*Bharat Institute Of Engineering And Technology*	Smart Blind Assistant Glasses
Mandadi Neeraj Reddy Tawseef Ahmad Ch. Sunil Kumar M. Suresh	*Bharat Institute Of Engineering And Technology*	Satellite Image Segmentation For Urban Planning
Rahhou Abd Elaziz	*Cadı Ayyad Unıversıty*	Dinuclear Metal Complexes As Recyclable Catalysts In Organic Synthesis

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SESSION-2, HALL-1 / OTURUM-2, SALON-1

MODERATOR: Ömer Sözen

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Mehmet Fırat Baran Erhan Kahya	*Siirt University*	Computer-Based Approach For Measuring The Length And Weight Of Cucumbers (Cucumis Sativus L.) Using Yolov8
Aslıhan Kevser Bengisu Odluyurt Korkmaz Bellitürk Mehmet Fırat Baran	*Siirt University*	Nutrient Composition of Vermicompost
Ercan Ceyhan Serdar Karadaş	*Selcuk University*	Breeding And Quality Improvement Strategies For Plant Protein Demand In Legumes: Modern Approaches And Future Perspectives
Serdar Karadaş Ercan Ceyhan	*Selcuk University*	Legumes In The Age Of Global Warming: Physiological Stress Responses And Production Risks
Ercan Ceyhan Serdar Karadaş	*Selcuk University*	Evaluation Of Legumes In Terms Of Nutritional And Technological Quality In The Context Of Sustainable Alternative Protein Sources
Ercan Ceyhan Serdar Karadaş	*Selcuk University*	Economics of Plant Breeding: Optimization and Cost–Benefit Framework
Ercan Ceyhan Serdar Karadaş	*Selcuk University*	Strategic Management of Plant Breeding in Türkiye: National Framework and Innovation Ecosystem
Irem Ayran Çolak Veysel Tokur	*Selcuk University*	Mineral Content, Antioxidant Activity And Bioactive Compounds Of Fennel (Foeniculum Vulgare) Grown Under The Ecological Conditions Of Konya
Ömer Sözen Tolga Karaköy	*Sivas University of Science and Technology*	Determination Of Agronomic Characteristics Of Some Lentil Genotypes
Tolga Karaköy Ömer Sözen	*Sivas University of Science and Technology*	Determination Of Quality Characteristics Of Some Lentil Varieties
Yeter Çilesiz Seyithan Seydoşoğlu	*Sivas University of Science and Technology*	Genomic And Transcriptomic Approaches For Lentil Breeding
Yeter Çilesiz Seyithan Seydoşoğlu	*Sivas University of Science and Technology*	Omics-Based Analysis of Abiotic and Biotic Stress Responses and Multilayer Network Models in Lens culinaris
Yeter Çilesiz	*Sivas University of Science and Technology*	Targeted Gene Editing in Plant Breeding Using Crispr–Cas9

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SESSION-2, HALL-2 / OTURUM-2, SALON-2

MODERATOR: Buse Apaydin

Meeting ID: 929 9691 8209
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AUTHOR	AFFILITION	ABSTRACT TITLE
Nur Kılınç Mehmet Kılınç	*Giresun University*	Dyeing Of Biomordanted Fabrics With Microwave Energy And Analysis Of Color Properties
Yunus Kaya	*Bursa Technical University*	Design And Modeling Of Next-Generation Grinding Aids And Investigation Of Their Effects
Yunus Kaya	*Bursa Technical University*	Experimental And Theoretical Investigation Of The Ftir And Nmr Spectra Of The Ester Molecule Obtained From The Synthesis Of Acetic Acid And Tipa
Gaye Özata Inyayla Şule Ocak Araz	*Kırıkkale University*	Effect Of Fillers Reinforced In Polyamide-6 Matrix On Thermal Conductivity
Ilgın Ayazgün Yusuf Özçatalbaş	*Gazi University*	Investigation Of Sintering And Alloying Behavior Of Prealloy + Premixed Alumix 123 Powder
Buse Apaydın Yusuf Özçatalbaş	*Gazi University*	The Effect Of Compaction Pressure And Sintering Temperatures On The Mechanical Properties Of Tm Parts Produced With Pre-Alloyed And Mixed Alumix 123 Powder
Tayfun Gül Özkan Coruk	*Kocaeli University*	Deterministic And Probabilistic Analysis Of Wedge Sliding Potential In Rock Slopes

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SESSION-2, HALL-3 / OTURUM-2, SALON-3

MODERATOR: Assiya Atif

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Md. Rafiqul Islam Mohammad Lokman Ali Sabrina Akter Rinju Sudipta Kumar Nag Tridip Roy Tawhidur Rahman Hafijur Rahman	*Patuakhali Science And Technology University*	Comparative Assessment Of Growth Performance And Survival Rate Of Mono-Sex And Mixed-Sex Nile Tilapia (Oreochromis Niloticus) In Cage Culture Systems: Evidence From Southern Bangladesh
Assiya Atif Soukaina Ameur Houssine Ait Sir	*Chouaib Doukkali University*	Synthesis, Characterization, And Computational Investigation Of 2,5-Bis(2-Methyl-1h-Benzimidazol-5-Yl)-1,3,4 Oxadiazole: Quantum Chemical Analysis, Adme Prediction, Molecular Docking, And Md-Based Corrosion Study For Photonic And Therapeutic Applications
Syful Islam Abdullah Bijoy Aliar Rahman Rakhi Chowdhury Khan Shaiful Islam	*Bangladesh Agricultural University,*	Fermentation Efficiency Of Rice Bran, Rice Polish, And De-Oiled Rice Bran For Nutritional Upgrading And Bioethanol Production
Yassir Khalsi Mehdi Mennani Zineb Kassab	*Mohammed Vi Polytechnic University*	Low-Temperature Catalytic Graphitization For High Performance Carbon Materials
Sathwik Babu N M.Suresh Kanimozhi R Syeda Hifsa Naaz	*Bharat Institute Of Engineering And Technology*	Neo Face - Ai-Powered Face Reconstruction
Ahmed Osmane Khadija Zidan Moustapha Belmouden	*Agadir University Ibn Zohr*	Sustainable Millet For Food And Feed Production In Semi-Arid Climates: Utilizing Trickling Filter-Treated Wastewate
Idris B. Allinson Temilade A. Olatunji	*1 Federal Polytechnic, Ilaro, Department Of Agricultural Technology, Ogun State*	Harvesting Urban Wisdom: A Policy Blueprint For Sustainable Nigeria Inspired By Latin America's Tales And Ecological Echoes
Sayeda Humaira Tanjum Mohammad Mehedi Hasan Khan Rubaiat Nazneen Akhand	*Sylhet Agricultural University*	Phytochemical, Biochemical And Antimicrobial Characteristics Of Cinnamon, Clove, Cardamom And Black Pepper

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SESSION-2, HALL-4 / OTURUM-2, SALON-4

MODERATOR: Prial Chowdhury

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Zakariya Alam Bappi Apon Chandra Paul Shohan Ali Sagor Gharami Nur Ullah Shadin Avinandan Paul Seemanto Mohammad Abu Hena Mostofa Jamal Rezuanul Islam	*Islamic University*	Plant-Mediated Green Synthesis Of Silver Nanoparticles Using Coleus Amboinicus (Mexican Mint) To Control Multidrug Resistance Pathogen Of Post-Covid Patient's Respiratory Tract Infection: An Integrated Experimental, Molecular Docking, And Molecular Dynamics Simulation Study
Wissem Belkheir Wafa Tebboune Zahra Bounouara Fatima Zohra Hadjadj	*University Of Sciences And Technology Of Oran-Mohamed Boudiaf*	A Microscopic Analysis Of Shared Lane Capacity Under Variables Green Time And Heterogeneous Turning Traffic Movements
G. M. S. I. Azad M. R. N. Alam M. Ashikuzzaman M. R. Rahman M. A. Alim	*Sichuan Road &Amp; Bridge (Group) Corporation Ltd.*	Effect Of Rainfall On Slope Stability Using Finite Element Method (Fem): A Case Study In Rangamati, Bangladesh
Tanmoy Datta Md. Moznuzzaman	*Jashore University Of Science And Technology*	Comparative Wavelet-Based And Conventional Filtering Techniques For Surface Emg Assessment In Low Back Pain Patients
Mahmud, M.R.A. Alam, M.S.	*Bau*	Genetic Diversity And Population Structure Of Climbing Perch (Anabas Testudineus) Collected From Southeast Asia Based On Mitochondrial Cytochrome C Gene Sequence Analysis
Prial Chowdhury	*University Of Chittagong*	Magnetic Graphene Oxide (Mgo): The Best Solution For Removing Heavy Metals From Water
Asifa Noor Shafiqul Islam Syful Islam	*Khulna University*	Comparative Effects Of Conventional And No-Tillage Systems On Soybean Productivity And Seed Composition Under Moderate Salinity
Diganta Bose Ritu Mondal Md. Moznuzzaman	*Jashore University Of Science And Technology*	Design Of Non-Adaptive Filtering And Wavelet Transform Techniques For Emg Noise Reduction
Rubaiatul Islam Zerin Kamrul Hossain Iffat Ara Umee Habiba Tini Faria Islam Akib Javed Anisul Kabir	*Islamic University*	E-Waste Generation And Disposal Practices In Urban Bangladesh: A Case Study Of Kushtia Municipality

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SESSION-2, HALL-5 / OTURUM-2, SALON-5

MODERATOR: Jai Gopal Gupta

Meeting ID: 929 9691 8209
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AUTHOR	AFFILITION	ABSTRACT TITLE
Jai Gopal Gupta	*National Institute Of Technology Sıkkım*	Simulation-Based Evaluation Of Methanol-Diesel Blends In Ci Engines Using Ansys: Performance And Emission Insights
Valavala Prashanthi Juveria Nargis Palepu Naga Sridharbabu M.Suresh	*Bharat Institute Of Engineering And Technology*	Ai For Qr Code Safety
Valer Bocan Valentin Stângaciu Cristina Stângaciu Flavius Oprițoiu Teodor Petrița Florin Alexa Cristian Spătaru Dan Leşeanu	*Politehnica University Timişoara*	Development Of A Modular Covert Audio-Video Surveillance System For National Security Applications Using 4g/5g Transmission
Hossain Tamim A Datta, Narayan A. Saha, Anik A Chowdhury, Bappy A Habibulla, Mohammad A Fahima, Atika Rifat A Taki, Tajnim B Sarwatun, Mohima B Roy, Dola B Faisal, B Tasnim, Farhana	*Chattogram Veterinary And Animal Sciences University*	Transforming Dairy Whey Byproducts Into A Nutritious Mango-Infused Functional Beverage: Formulation, Nutritional Value, And Sensory Acceptance
Djihane Romayssa Mahammed Nabila Belyagoubi-Behnhammou Asmaa Dich Larbi Belyagoubi Sarra Benaissa Kamal Benmansour Gabriele Di Marco Alessia D'agostino Antonella Canini Angelo Gismondi	*University Of Tlemcen*	Development And Characterization Of Bioactive And Smart Biofilms Based On Plant Extracts And Oils For Sustainable Material Applications
Mizanur Rahman Nasir Uddin Wazid Ahmed Razi	*Daffodil Institute Of It(Diit)*	Guardnex - Advanced Multilingual Spam Detection Platform
Apurbo Kumar Biswas Khadija Akter Akhi Rahima Nasrin	*University Of Barishal*	Structural And Optical Characterization Of Cbd Deposited Copper Sulphide Thin Films

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SESSION-3, HALL-1 / OTURUM-3, SALON-1

MODERATOR: Zeynep Yumlu

Meeting ID: 929 9691 8209
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AUTHOR	AFFILITION	ABSTRACT TITLE
Aleyna Aydemir Gizem Yıldırım Baştemur Sabriye Perçin Özkorucuklu	*Istanbul University*	Evaluation Of The Phytochemical Profile And Antioxidant Activity Of Stevia Rebaudiana Bertoni
Özlem Pelin Can Meryem Göksel Saraç Tuğba Dedebaş	*Afyon Kocatepe University*	The Effect Of Bitter Lupin (Lupinus Albus) Addition On The Physical, Microbiological And Sensory Properties Of Beef Meatballs
Özlem Pelin Can Meryem Göksel Saraç Tuğba Dedebaş	*Afyon Kocatepe University*	The Effect Of Hemp Powder On Yogurt Quality Parameters
Pınar Gümüş	*Kilis 7 Aralik University*	A Valuable Marine-Based Omega-3 Source: Antarctic Krill Oil
Eda Elgin Kılıç Songül Kesen	*Gaziantep University*	Effects Of Microencapsulation On The Stability Of Phenolic And Antioxidant Compounds In Functional Food Systems
Zeynep Yumlu Durmuş Erdurmuş Emre Evlice	*Sivas University Of Science And Technology*	Biocontrol Potential Of Clonostachys Rosea Isolates Against Selected Soil-Borne Fungal Pathogens Of Lettuce
Ferda Gizem Bal Zeynep Yumlu Emre Evlice	*Sivas University Of Science And Technology*	Plant Parasitic Nematodes Causing Damage In Ornamental Plants
Çağlar Doğan	*Istanbul University*	Mechanisms Of Mass Generation For Neutrinos In Su(5) Grand Unified Theories

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SESSION-3, HALL-2 / OTURUM-3, SALON-2

MODERATOR: Selinay Gümüş

Meeting ID: 929 9691 8209
Passcode: 272829

AUTHOR	AFFILITION	ABSTRACT TITLE
Ali Akay Fatih Güven	*Hacettepe University*	Mechanical Performance Assessment For Multipass Welding Of Dissimilar S690ql And S355j2+N Materials Using G4si1 Filler Wire
Nazlı Keklik Cinkara Deniz Adıgüzel Serkan Tüylü Ismail Demir	*Istanbul University*	Environmental Management And Cyanide Removal Of Gold Mine Cyanide-Bearing Wastes
Serkan Tüylü Deniz Adıgüzel Ismail Demir	*Istanbul University*	Evaluation Of Geotechnical Properties Of Clay Materials For Use In Tailings Storage Facilities
Selinay Gümüş Ayşe Aytaç	*Kocaeli University*	Development Of Bio-Polyester Polyols For Water-Based Bio-Polyurethanes
Kübranur Ağtoprak Uğur Karaaslan	*R&D Specialist*	Sustainable Alternative Corrosion Inhibitors For Engine Coolant Fluids
Çağla Taşkın Uğur Karaaslan	*R&D Engineer*	Improvement Of Boundary Lubrication Characteristics With Different Ester Types

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SESSION-3, HALL-3 / OTURUM-3, SALON-3

MODERATOR: Mourad Aloui

Meeting ID: 929 9691 8209
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AUTHOR	AFFILITION	ABSTRACT TITLE
Zahra Najidi Mohammed Elkabous Mostafa Khouili	*Sultan Moulay Slimane University*	Synthesis, Characterization, And Antimicrobial Photodynamic Activity Of Porphyrin–Indazole Hybrids
Rajveer Sarup Palak Kumari	*Bsc Biotechnology, Ct Group Of Institutions*	Oyster Mushrooms: Therapeutic Significance In Cvd
Abdurrahman Idris	*Umaru Musa Yaradua Unıversıty*	Machine Learning Approaches For Predicting Quantum States In Simple Quantum Systems
Mohammed Elkabous Yasser Karzazı	*University Of Mohammed Premier*	Impact Of The Hubbard U Parameter On The Optoelectronic Response Of Anatase TiO_2 Within Dft+U Calculations
Mourad Aloui Elhalaoui Menana	*Sidi Mohamed Ben Abdellah University*	In Silico Design Of Novel Dihydropteridone Derivatives With Oxadiazoles As Potent Inhibitors Of Mcf-7 Breast Cancer Cells
Swarnali Akter	*University Of Rajshahi*	Geospatial Modeling Of Urban Flood Vulnerability In Dhaka City: An Integrated Remote Sensing, Gis, And Ahp-Fuzzy Smce Approach
Razia Sultana Ruba	*University Of Rajshahi*	Climate Change And Anthropogenic Waterlogging: Small Farmers' Vulnerability To Food Security In Barind Area Of Bangladesh
Chandani Sharma Dr Jai Singh	*Deemed To Be University*	Re -Processing Of Melon By - Products For A Variety Of Valorized Products
Aboubacar Sidigh Sylla Aziz Ihammi Ilham Kirm Abdelghani Boussetta Kamal Benali Tarik Ainane Nour-Eddine El Mansouri Mohammed Chigr	*Sultan Moulay Slimane University*	Utilization Of Olive Mill Solid Waste-Based Activated Carbon For The Effective Elimination Of Phenolic Compounds In Olive-Mill Wastewater: A Study On Optimization, Kinetics, And Isotherms
Muhammed Işık Selda Uzal Seyfi	*Selçuk University*	Greenhouse Potential Of Konya Province And Different Greenhouse Practices

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Aslı Kaçar Zekiye Erdoğan Gökhan Erdoğan Baran Aslan Aylin Kabaş Ibrahim Çelik Selman Uluışık	Assessment Of Tetranychus Urticae Tolerance In Tomato Lines Derived From Solanum Pennellii (La0716)	3
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ABSTRACT

ON NEIGHBORHOOD-BASED TOPOLOGICAL INDICES IN QUANTITATIVE STRUCTURE–ACTIVITY RELATIONSHIP ANALYSIS OF SOME FDA-APPROVED ANTICANCER AGENTS

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ABSTRACT

Cancer, one of today's most significant health issues, is a disease caused by uncontrolled cell proliferation. Early diagnosis, appropriate treatment approaches, and new-generation research play a vital role in the fight against cancer. A study of drugs used to treat cancer has sparked interest, especially through the use of topological indices based on molecular properties. A deeper understanding of these properties is crucial for drug development. topological indices help bridge the gap between the chemical and pharmaceutical industries by offering an affordable way to determine the molecular properties. This study examines some FDA-approved drugs used to treat cancer, one of the most prevalent diseases worldwide. Quantitative structure activity relationship analysis is performed to determine the relationship between indices and drug properties like heavy atom count, exact mass, molar refractivity, complexity, and polarizability. The study considers the neighborhood geometric-arithmetic index, neighborhood Randic index, neighborhood reverse Randic index, neighborhood atom-bond connectivity index, neighborhood nirmala index, neighborhood reduced reciprocal Randic index, and neighborhood inverse sum indeg index. The topological indices applied to these drugs are found to correlate well with physicochemical properties. This study clarifies the relationship between molecular structure and physicochemical properties by comparing them to evaluate the effectiveness of indices, and emphasizes the application of linear regression models to effectively predict these properties.

Key Words: Linear QSPR model, Drugs, Chemical graphs, Degree-based topological indices.
Acknowledgements: This study was supported by Bursa Uludağ University Research Projects Coordination Office under the Grant Number FGA-2025-2068. The authors thank to BUU BAP Unit for their supports.

LIGHTWEIGHT MACHINE LEARNING FOR DDOS ATTACK DETECTION IN RESOURCE-CONSTRAINED SMART HOME ENVIRONMENTS: A HYBRID APPROACH USING FEATURE SELECTION AND COMPARATIVE MODEL ANALYSIS

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ABSTRACT

This study presents a lightweight machine learning framework for detecting Distributed Denial of Service (DDoS) attacks in highly resource-constrained smart home IoT devices (80–200 MHz CPUs, 32–128 KB RAM). By combining simulation and physical test bed validation, the proposed hybrid approach leverages feature selection and algorithm optimization to minimize overhead while maintaining detection efficacy. A seven-feature subset achieved 94.6% of the full model's accuracy with a 76.4% reduction in computational load. Three optimized classifiers—Decision Tree (1.37 KB, 94.8% accuracy), Random Forest (6.82 KB, 96.3%), and Naïve Bayes (0.92 KB, 91.7%)—were developed using techniques like fixed-point arithmetic, information gain-based tree construction, and early termination logic. The distributed architecture reduces device-level processing by up to 78% with sub-100ms detection latency. Experiments show high accuracy against volumetric attacks (>95%) and strong performance against application-layer attacks (>80%), with low battery impact (5–13%). This work demonstrates that hardware constraints in smart homes can be effectively addressed through tailored ML design, enabling practical security solutions.

Keywords: DDoS attack detection, resource-constrained environments, lightweight machine learning, smart home security.

ASSESSMENT OF *TETRANYCHUS URTICAE* TOLERANCE IN TOMATO LINES DERIVED FROM *SOLANUM PENNELLII* (LA0716)

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ABSTRACT

In Turkey, the two-spotted spiders mites (*Tetranychus urticae* Koch) is a serious and economically important pest on vegetables, fruits, and field crops cultivate both in open fields and greenhouses. Commercial tomato varieties (*Solanum lycopersicum* L.) exhibit pronounced susceptibility to this pest. An increase in the population of *T. urticae* can alter the morphological appearance of tomato leaves and fruits, resulting in economic losses. Insecticides are employed to this pest, however the extensive application of these pesticides has facilitated the development of resistance among *T. urticae* populations. Therefore, the idendification of resistant plant lines is essential for effective control of *T. urticae* in tomato cultivation. In the previous step of the study, the free-choice method was used to determine the plants preferred and not preferred by *T. urticae* in the F2 populations obtained from the cross between the tolerant species *S. pennellii* (LA0716) and the susceptible AK2082 (*S. lycopersicum*). In this

method, 200 female adult mites were placed in the center of the tray, equidistant from all plants, using a brush. Their orientation was observed simultaneously among 208 83F2 plants. Subsequently, leaves were collected from all plants, and spiders' preference was determined using an olfactometer, and spiders numbers were calculated. Finally, the trichomes were counted. Morphological findings from the three stages suggest that plants with short stature, narrow leaves, and high hairiness may be resistant to *Tetranychus urticae*. DNA samples were taken from each *S. pennellii* (LA0716) × *S. lycopersicum* (AK2082) plant and transferred to the greenhouse for further examination.

Keywords: Two spotted spiders mites, tomato, resistance

Acknowledgements: This project is supported by The Scientific and Technological Research Council of Turkey (TUBITAK) under project number 124O825.

BAL ARILARINDA (*Apis mellifera*) VARROA DESTRUCTOR İLE MÜCADELEDE KULLANILAN LİTYUM KLORÜRÜN BALDA KALINTI SEVİYELERİNİN BELİRLENMESİ

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ÖZET

Bu çalışmanın amacı Türkiye arıcılığına en büyük zararı veren varroa paraziti üzerine etkili lityum klorür maddesinin iki farklı dozda (10 ve 25 mM) ve üç farklı metod (fondan şeker, şeker spreyleme ve şerbetleme) ile saha koşullarında uygulanması sonucu elde edilen ballarda lityum kalıntı seviyelerinin tespit edilmesidir. Bu çalışmada toplam 70 arılı kovan kullanılarak lityum klorürün 10 ve 25 mM konsantrasyonları; 10 mM lityum klorür fondan şeker ile, 25 mM lityum klorür fondan şeker ile, 10 mM lityum klorür şerbet spreyleme (pulvarize) ile, 25 mM lityum klorür şerbet spreyleme (pulvarize) ile, 10 mM lityum klorür şerbetleme ile, 25 mM lityum klorür şerbetleme ile olacak şekilde toplamda üç farklı uygulama yapılmıştır. Bu çalışmada uygulama sonrası alınan bal örneklerinde yapılan analizler sonucu lityum klorür ortalamaları 10 mM lityum klorür fondan şeker 22,22 mg/kg, 25 mM lityum klorür fondan şeker 58,285 mg/kg, 10 mM lityum klorür şerbet spreyleme (pulvarize) 16,255 mg/kg, 25 mM lityum klorür şerbet spreyleme (pulvarize) 37,01 mg/kg, 10 mM lityum klorür şerbetleme 13,424 mg/kg, 25 mM lityum klorür şerbetleme 52,965 mg/kg olarak tespit edilmiştir.

Anahtar Kelimeler: Bal, Bal Arısı, Lityum Klorür

DETERMINATION OF LITHIUM CHLORIDE RESIDUE LEVELS IN HONEY USED FOR THE CONTROL OF VARROA DESTRUCTOR IN HONEYBEES (APIS MELLIFERA)

ABSTRACT

The aim of this study is to determine the lithium residue levels in honey obtained as a result of the application of lithium chloride, which is effective against the varroa parasite that causes the greatest damage to beekeeping in Turkey, at two different doses (10 and 25 mM) and with three different methods (fondant sugar, sugar spraying and syruping) under field conditions. In this study, a total of three different applications were made using 70 beehives and 10 and 25 mM concentrations of lithium chloride; 10 mM lithium chloride with fondant sugar, 25 mM lithium chloride with fondant sugar, 10 mM lithium chloride syrup spraying (pulverized), 25 mM lithium chloride syrup spraying (pulverized), 10 mM lithium chloride syrup, and 25 mM lithium chloride syrup. In this study, as a result of the analysis made on honey samples taken after the application, the average lithium chloride levels were determined as 10 mM lithium chloride fondant sugar 22.22 mg/kg, 25 mM lithium chloride fondant sugar 58.285 mg/kg, 10 mM lithium chloride syrup spraying (pulverized) 16.255 mg/kg, 25 mM lithium chloride syrup spraying (pulverized) 37.01 mg/kg, 10 mM lithium chloride syrup 13.424 mg/kg, 25 mM lithium chloride syrup 52.965 mg/kg.

Keywords: Honey, Honeybee, Lithium Chloride

QSPR ANALYSIS OF ANTICANCER COMPOUNDS USING NEIGHBORHOOD SOMBOR AND RELATED TOPOLOGICAL INDICES

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ABSTRACT

Cancer is a significant global health problem, which necessitates the development of effective therapeutic agents and reliable computational approaches for predicting their properties. In this regard, mathematical and graph-theoretical tools have gained importance in drug design and development, offering efficient ways to model and predict the behavior of complex molecular structures. Topological indices (TIs), defined as numerical descriptors derived from molecular graphs, are widely employed to characterize chemical systems and to investigate the physicochemical properties and biological activities of pharmaceutical agents. As experimental determination of these properties is costly and resource-intensive, TIs provide a mathematical alternative that effectively bridges the fields of chemistry and mathematics. This renders them valuable tools in the realm of drug design and development. In this study, a range of anticancer drugs are analyzed using quantitative structure–activity relationship (QSPR) methods. The objective of this study is to establish mathematical relationships between topological indices and key physicochemical properties. The properties investigated included polar surface area, complexity, molar volume, molecular weight, and polarizability. The findings indicate the presence of robust correlations, particularly for indices based on neighborhood degree, which demonstrate a high degree of predictive capability. Moreover, a comparison between calculated and experimental values emphasizes the efficacy of the applied indices. This study will provide a comprehensive overview of the relevant literature on the subject.

Key Words: Cancer, Graph Theory, Topological Indices, QSPR.

Acknowledgements: This study was supported by Bursa Uludağ University Research Projects Coordination Office under the Grant Number FGA-2025-2068. The authors thank to BUU BAP Unit for their supports.

SOME EDIBLE MACROFUNGI DETECTED IN VAN YUZUNCU YIL UNIVERSITY CAMPUS AND SURROUNDING AREA (VAN, TURKEY)

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ABSTRACT

Mushrooms are highly important for health as they have low calorie in addition to ingredients such as high protein, vitamin and nutrients. Of all the food, they are among the best vegetables and animal protein sources. The present study is aimed to contribute the mycobiota of Turkey as well as to raise the public awareness of the region about edible. Moreover, fungus can be handled as an alternative nutrient to lack of food for growing population of the world. The material of the study consists of macrofungal samples collected within the borders of Van Yuzuncu Yil University Campus and Surrounding Area between 2023-2025. The morphological and ethnomycological characteristics of macrofungi were determined and recorded. Their photographs were also taken in their natural environments and substrates. After the microscopic characteristics of the macrofungi taken to the laboratory were determined, the materials were identified according to the data obtained. As a result of the study, 39 edible macrofungus taxa belonging to Agaricomycetes and Pezizomycetes classes were determined.

Keywords: Macrofungi, Edible, Van, Turkey.

Acknowledgment: The author would like to thank Van Yüzüncü Yıl University Research Fund for supporting the project (FYL-2024-11273).

OPTIMIZATION OF LEAD LUG RATIO FOR ENHANCED TRACTION AND WEAR PERFORMANCE IN AGRICULTURAL VEHICLES

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ABSTRACT

The efficient operation of agricultural vehicles depends not only on engine power but also on how effectively that power is transmitted to the ground. In this context, the Lead/Lug ratio defined as the rotational lead of the front wheels relative to the rear wheels is a critical parameter, especially in tractors equipped with MFWD (Mechanical Front Wheel Drive) systems. This ratio directly affects traction performance, fuel consumption, transmission lifespan, and soil health. In MFWD tractors, the front wheels are typically smaller in diameter than the rear wheels. The Lead/Lug ratio plays a vital role in optimizing power transfer, fuel efficiency, and tire longevity. Therefore, a specific lead ratio is required to ensure synchronized rotation between the front and rear wheels [1, 2]. This study investigates the effect of the Lead/Lug ratio on traction efficiency and wear performance in agricultural vehicles equipped with MFWD systems. Based on factory-level testing, the rolling circumferences of tires under static and dynamic loads were measured, allowing for theoretical calculation of rotational ratios. The results indicate that a lead ratio between 1% and 5% provides the best balance between traction gain and minimal wear. According to finite element analysis and semi-empirical modeling confirms that proper lead settings can improve traction by up to 12% [2]. As a conclusion, the data-driven framework for integrating Lead/Lug optimization into tire design and tractor configuration strategies.

Keywords: Agricultural vehicles, Lead/Lug ratio, MFWD systems, Rolling circumference, Tire optimization

RELATIONSHIP OF RRC-TEMPERATURE-SPEED ON TRUCK AND BUS TIRES (22.5 SIZES)

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ABSTRACT

Rolling Resistance Coefficient (RRC) is a critical parameter in terms of tire energy efficiency, performance, and environmental impact. This study quantitatively investigates the relationship between RRC, temperature, and speed in Truck and Bus-22.5 sized commercial vehicle tires through indoor tests conducted in accordance with the ISO 28580 standard. Under constant load (85% LI) and nominal inflation pressure, measurements were taken on 16 different tires at speeds of 30, 50, and 80 km/h. The temperature differences between the beginning and end of the tests (ΔT) and the corresponding RRC values were analyzed. The results reveal that RRC does not exhibit a linear relationship with temperature or speed. Notably, the lowest average RRC value observed at 50 km/h indicates an optimal operating point where viscoelastic energy losses and convective cooling effects are balanced. As speed increases, internal temperature rises, but this increase does not always lead to a reduction in RRC. The slope (β) of the ΔT–RRC curves varies with speed regime, indicating that tire viscoelasticity is influenced jointly by temperature and frequency (speed). By modeling the temperature–RRC relationship not with a single fixed slope but with speed-band-specific sensitivities, the study offers meaningful predictions in the context of field-relevant speed profiles and thermal transition processes. These findings suggest that failure to jointly evaluate tire thermal state and operational speeds in regulatory simulations such as VECTO may result in deviations in fuel consumption estimates. Furthermore, the 50 km/h speed band is highlighted as having the highest potential for gains in energy efficiency and sustainable transportation strategies.

Keywords: Rolling resistance, temperature, speed, commercial vehicle tire, thermoviscoelasticity, ΔT, β_v.

INVESTIGATION OF MICROPLASTIC PRESENCE IN TAP WATERS IN ISTANBUL

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ABSTRACT

Microplastics, due to their unique physicochemical properties, demonstrate high resistance to environmental degradation and have emerged as pervasive micro-pollutants worldwide. While numerous studies have investigated the presence of microplastics in drinking water by sampling at the inflow and outflow points of water treatment plants, there is a notable scarcity of research examining the water that is directly delivered to consumers via household and public taps. This gap is particularly evident in Turkey, where no prior studies have addressed this issue. To bridge this gap, tap water samples were collected over the course of one month from five different districts using a specially designed, fully enclosed sampling device. This device is engineered to minimize contamination and facilitate the collection of large volumes of water, a critical feature given the typically low concentrations of microplastics found in tap water. Preliminary analysis of the collected samples, conducted through visual inspection and Raman spectroscopy, confirmed the presence of microlitter in every sample, with several particles identified as microplastics. The ability to obtain large-volume samples proved essential to securing representative and statistically meaningful data. These findings highlight the widespread occurrence of microplastics in tap water and underscore the necessity for continuous monitoring at the consumer endpoint. This study contributes valuable baseline data to a limited research area and provides a robust methodological framework for future investigations into human exposure and potential health impacts related to microplastics in drinking water.

Keywords: Microplastics, Tap Water, Water Quality

INVESTIGATION OF CYTOTOXIC AND APOPTOTIC EFFECTS OF *ALCHEMILLA CAUCASICA* BUSER EXTRACTS ON HUMAN MCF-7 CELL LINE

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ABSTRACT

Alchemilla caucasica Buser, a species belonging to the *Rosaceae* family, is naturally distributed in the Caucasus region encompassing Turkey, Georgia, and Armenia. Various studies have revealed that *Alchemilla* species contain numerous pharmacologically active compounds, primarily terpenes, tannins, and flavonoids. These flavonoids, in particular, exhibit potent antioxidant, antiinflammatory, antibacterial, antiviral, and anticancer properties. A literature review reveals that research on the cytotoxic effects of *Alchemilla caucasica* is quite limited, suggesting that future studies in this area will fill a significant gap. In this regard, our study investigated the cytotoxic and apoptotic effects of extracts obtained from the leaves and stems of *Alchemilla caucasica* on the MCF-7 breast cancer cell line. First, the effect of the extract on cell viability was determined by the MTT method. Then, the proapoptotic (Bax) and antiapoptotic (Bcl-2) gene expression levels in cells treated with the extract were determined by the RT-QPCR method. In this study, *Alchemilla caucasica* extract was applied to MCF-7 cell line at different concentrations for 24 and 48 hours. According to the MTT test results, after 48 hours of exposure to *Alchemilla caucasica* extract, cell viability in the leaf part was found to be 57% ($P<0.0001$) starting from a dose of 500 µg/mL, and cell viability was observed at doses below this dose. After 48 hours of exposure to *Alchemilla caucasica* extract, cell viability in the stem part was found to be 50% ($P<0.0001$) starting from a dose of 1000 µg/mL. Furthermore, it was determined that stem and leaf extract applied at a concentration of 250 µg/mL for 48 hours increased Bax gene expression levels in MCF-7 cells. Bcl-2 gene expression levels decreased with 250 µg/mL leaf extract and increased with stem extract. We believe the findings will highlight new supportive approaches for breast cancer treatment

Keywords: *Alchemilla caucasica* Buser, MCF-7, cell culture, cytotoxic activity, apoptotic effect.

NEUROPROTECTIVE EFFECT OF A NOVEL BENZIMIDAZOLIUM DERIVATIVE: AN APPROACH THROUGH DNMT-MEDIATED EPIGENETIC REGULATION

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ABSTRACT

Neurodegenerative diseases (ND) are a group of diseases characterized by progressive neuronal loss, synaptic dysfunction, and cognitive or motor impairments, and are not yet fully treatable. Oxidative stress, mitochondrial degradation, protein aggregation, and epigenetic changes are among the primary causes of neuronal death in these diseases. The role of epigenetic mechanisms, particularly DNA methyltransferase (DNMT) enzymes, in the development of NDs is gaining increasing importance. DNA methylation plays a critical role in regulating neurological functions such as brain development, synaptic plasticity, learning, and memory. This study investigated the role of newly synthesized benzimidazolium salt (BS) on epigenetic mechanisms (especially DNMTs) against H_2O_2-induced neurotoxicity in neuron-like differentiated SH-SY5Y cells. First, retinoic acid was applied to SH-SY5Y cells to produce mature neurons. Then, a toxicity model was created by treating neuron-like differentiated SH-SY5Y (d-SH-SY5Y) cells with H_2O_2. The BS dose to be applied to d-SH-SY5Y cells in the study was decided by MTT assay. DNMT1, DNMT3a, and DNMT3b gene expression levels were determined by RT-qPCR. According to our findings, DNMT1, DNMT3a, and DNMT3b gene expression levels in the neurodegenerative model group (H_2O_2) showed a statistically significant increase compared to the control group (3.56; 4.48; 2.70 fold change, respectively). This increase indicates that the model activates cellular stress and gene silencing processes at the epigenetic level. In addition, 2.5 µM and 5 µM BS pretreatment significantly decreased DNMT1, DNMT3a, and DNMT3b gene expression levels in d-SH-SY5Y cells compared to the H_2O_2 group ($p<0.0001$). Our results suggest that BS pre-applied to cells exerts a neuroprotective effect by suppressing or normalizing DNMT-mediated epigenetic changes. Therefore, based on these data, we believe that BS can be considered a neuroprotective agent in ND models and provides preliminary data for assessing the role of other epigenetic mechanisms (histone modifications and non-coding ribonucleic acid regulation).

Keywords: DNMT, SH-SY5Y, Neurodegenerative diseases, Benzimidazolium salt

COLD STRESS RESPONSES IN GRAPEVINE: COMPARATIVE MORPHOPHYSIOLOGICAL AND BIOCHEMICAL TRAITS OF THREE CULTIVARS

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ABSTRACT

This study investigated the morphophysiological and biochemical responses of three *Vitis vinifera* L. cultivars (‘Muscat Italia’, ‘Michele Palieri’, and ‘Red Globe’) grown under two contrasting climatic environments during the 2023–2024 seasons. The experiments were conducted at two sites: one representing optimal climatic conditions and the other characterized by low winter temperatures. Cold stress markedly influenced vegetative growth, leaf anatomy, and physiological functions, with distinct cultivar-dependent responses. Shoot length, leaf area, stomatal density, and chlorophyll content decreased under cold conditions, whereas leaf temperature and cuticular wax accumulation increased. Stomatal conductance (gs) declined significantly, showing mean reductions of 40% in ‘Muscat Italia’, 36% in ‘Red Globe’, and 20% in ‘Michele Palieri’, with slight interannual variability. In contrast, the levels of biochemical compounds such as proline, total soluble sugars, flavonoids, and anthocyanins increased significantly in response to cold stress. Proline accumulation was particularly pronounced, rising by 98% in ‘Muscat Italia’, 72% in ‘Michele Palieri’, and 56% in ‘Red Globe’. Overall, the cultivar ‘Michele Palieri’ demonstrated superior tolerance and adaptive potential, making it a promising candidate for viticulture expansion in colder or mountainous regions under future climate change scenarios.

Keywords: *Vitis vinifera* L., cold stress, vegetative growth, physiological traits, biochemical compounds, cultivar adaptation.

INTELLIGENT SOLAR POWER FORECASTING USING HYBRID CNN-LSTM ARCHITECTURE: AN IOT-ENABLED EMBEDDED SYSTEMS APPROACH

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ABSTRACT

Solar photovoltaic (PV) systems have emerged as critical renewable energy sources, yet their intermittent generation patterns pose significant challenges for grid stability and energy management systems. This paper presents a novel hybrid Convolutional Neural Network-Long Short-Term Memory (CNN-LSTM) architecture integrated with an IoT-based embedded monitoring system for accurate, real-time solar power forecasting. The proposed system utilizes an ESP32 microcontroller-based hardware platform to collect real-time meteorological data including voltage, current, ambient temperature, and solar irradiance measurements. The CNN component effectively extracts spatial features and correlations from multi-dimensional sensor data streams, while the LSTM network captures complex temporal dependencies and time-series patterns essential for accurate forecasting. Experimental validation using two years of historical data from the Chennai region demonstrates superior performance with RMSE of 47.58 W/m2, MAE of 22.64 W/m2, and R2 of 96.94%, achieving 28.79% improvement over traditional Support Vector Regression methods and 4.56% improvement over standard LSTM networks. The embedded IoT system enables remote monitoring and predictive maintenance capabilities, reducing operational costs by 15-20% through optimized energy utilization and early fault detection. This integrated hardware software solution addresses critical challenges in renewable energy optimization and provides a scalable, cost-effective framework suitable for deployment in distributed solar microgrids and smart grid applications.

Keywords: Solar Power Forecasting · Deep Learning · CNN-LSTM · IoT · Embedded Systems · Smart Grid · Renewable Energy

ARTIFICIAL ORGANS AND 3D BIOPRINTING

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ABSTRACT
Artificial organs and 3D bioprinting represent groundbreaking advancements in modern biomedical science, offering transformative solutions for organ failure and tissue loss. Artificial organs—such as mechanical hearts, artificial kidneys, and bioengineered skin—aim to replicate the function of natural organs, reducing dependence on organ donors and lowering the risk of transplant rejection. With the emergence of 3D bioprinting, the field has rapidly evolved toward creating patient-specific tissues using biomaterials, living cells, and growth factors. This technology enables precise layer-by-layer fabrication of complex structures such as blood vessels, cartilage, liver tissue, and even early-stage heart constructs. The integration of computer-aided design, biocompatible scaffolds, and stem cell technologies has significantly improved tissue viability and structural integrity. Despite challenges like vascularization, immune response, and large-scale production, 3D bioprinting holds immense promise for regenerative medicine, drug testing, and personalized therapeutic applications. Together, artificial organs and 3D bioprinting are shaping a future where customized, functional organ replacements may become widely accessible, revolutionizing patient care and reducing the global burden of organ shortages.
Keywords: Artificial organs, 3D bioprinting, tissue engineering, regenerative medicine, biomaterials, stem cells, organ transplantation, bioink, scaffolds, vascularization, personalized medicine, biomedical engineering, organ fabrication, biocompatibility, medical biotechnology.

MECHANISMS AND THERAPEUTIC APPLICATIONS OF THE ANTIFUNGAL ACTIVITY OF TEA TREE OIL: A COMPREHENSIVE REVIEW

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ABSTRACT

Background: The increasing prevalence of fungal infections and rising antifungal drug resistance present urgent challenges for global health. Tea tree oil (TTO), extracted from the leaves of Melaleuca alternifolia, has emerged as a promising natural agent with notable antifungal, anti-inflammatory, and wound-healing properties. Objective: This review aims to provide a comprehensive analysis of the antifungal mechanisms and therapeutic applications of TTO and its primary monoterpene constituents, with focus on clinical and technological advancements. Methods: A systematic literature review was conducted using major scientific databases to identify recent studies on the antifungal activity, mechanistic pathways, and clinical applications of TTO and its constituent compounds such as terpinen-4-ol, 1,8-cineole, α-terpinene, p-cymene, and limonene. Criteria included studies with primary data, reports on mechanisms of action, and advancements in formulation strategies. Results: TTO exhibited potent antifungal effects against a broad spectrum of fungi, including Candida albicans, Aspergillus niger, and dermatophytes. The primary component terpinen-4-ol disrupts fungal cell membrane integrity, induces oxidative stress and mitochondrial dysfunction, and inhibits hyphal development and spore germination. Recent formulations, such as nanoemulsions and polymeric gels demonstrate enhanced stability, solubility, and skin penetration, further supporting TTO's clinical effectiveness. Comparative studies show TTO offers distinct advantages over traditional antifungals, including a reduced risk of resistance and synergistic efficacy. Conclusions: Tea tree oil and its monoterpenes possess multifaceted antifungal mechanisms, making them valuable candidates for adjunctive or alternative antifungal therapies. Ongoing research into optimized delivery systems and safety will help to solidify TTO's role in modern antifungal treatment, especially for drug-resistant and superficial mycoses.

Keywords: Tea tree oil, Melaleuca alternifolia, antifungal, terpinen-4-ol, mechanism of action, topical therapy, formulation, drug resistance.

GEOMECHANICS OF ANDESITIC ROCK UNITS IN THE GUNUNG GEULIS AREA, SUMEDANG REGENCY, INDONESIA

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ABSTRACT

This study evaluates the influence of weathering and rock discontinuities on the geomechanical behavior of andesitic rocks in the Gunung Geulis area, Sumedang Regency, Jatinangor, Indonesia. The region is characterized by complex volcanic lithologies, including andesitic lava, lapilli tuff, and agglomerates, affected by tropical weathering and structural deformation linked to regional fault systems. The research combines geological field mapping, systematic rock sampling, Schmidt hammer testing, and simulated laboratory analyses. A total of 60 rock samples 30 fresh and 30 weathered were collected from three slope sections. Laboratory simulations estimated key parameters such as uniaxial compressive strength (UCS), point load index, porosity, and unit weight following ASTM standards. The UCS of fresh rocks ranges from 60–120 MPa, while weathered samples exhibit significantly lower strength (15–40 MPa). Porosity increases and density decreases with weathering, confirming its weakening effect. Discontinuity analysis using DIPS software revealed joint orientations that align with slope faces, contributing to potential planar and wedge failures. Rock mass classification using RMR and GSI showed fair to poor rock mass quality, especially in weathered zones. These findings highlight the importance of lithology, weathering intensity, and discontinuity characteristics as key geomechanical controls. The results support slope stability assessments and can guide hazard mitigation, infrastructure planning, and further geotechnical research in similar volcanic terrains.

Keywords: Geomechanics, Andesitic rock, Weathering, Discontinuities, Slope stability

SURVEYING NOVEL PYRAZINE ACCEPTOR MATERIALS FOR BULK HETEROJUNCTION SOLAR CELLS: COMPUTATIONAL INSIGHTS INTO PHOTOVOLTAIC PERFORMANCE

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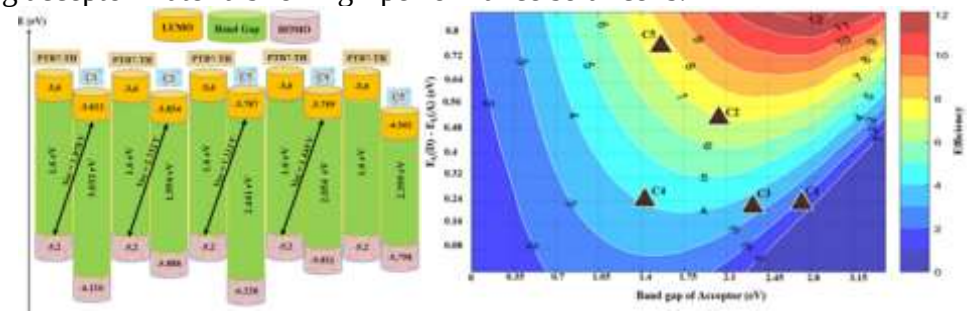
ABSTRACT

The design of organic electron acceptor materials is fundamental to advancing bulk heterojunction solar cells with outstanding photovoltaic performance. Among these, pyrazine-based π-conjugated electron acceptors have shown significant improvements over conventional acceptor materials, offering enhanced optoelectronic suitability, cost-effectiveness, and stability. In this comprehensive theoretical study, we investigate the potential of novel pyrazine derivatives (C1–C5) as acceptor materials in heterojunction solar cells. Using density functional theory (DFT) and time-dependent DFT (TD-DFT), we analyze key properties such as frontier molecular orbitals, density of states, electron and hole reorganization energies, molecular electrostatic potential, global reactivity descriptors, and photovoltaic parameters. The study further explores how variations in acceptor terminal groups influence the electronic and photovoltaic behavior of the designed compounds. The results indicate that the C1–C5 derivatives exhibit excellent optical properties, low bandgaps, optimal open-circuit voltages, and energy level alignment with the PTB7-Th donor polymer—highlighting their potential as promising acceptor materials for high-performance solar cells.



PREDICTING AIR QUALITY: MACHINE LEARNING (ML) MODELS FOR PM2.5 CONCENTRATIONS IN DELHI, INDIA

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ABSTRACT

Air quality is a critical indicator of environmental and public health in Delhi, India, where rapid urbanization and persistent emission sources contribute to highly variable air quality conditions. Traditional monitoring approaches provide essential observations but often fail to capture the complex interactions among meteorological parameters, emission patterns, and seasonal variability. This study aims to develop a robust predictive framework for PM2.5 concentrations in Delhi, India, using a comprehensive dataset of 7,697 samples collected over a year. The dataset includes 10 environmental parameters (Carbon Monoxide (CO), Nitric Oxide (NO), Nitrogen Dioxide (NO_2), PM2.5, and PM10, etc.) as well as 13 meteorological parameters (temperature, relative humidity, wind velocity, and atmospheric pressure, etc.). Three ML classifiers such as Random Forest (RF), Decision Tree (DT), and XGBoost, were employed, and their performance was evaluated using metrics such as accuracy, Mean Squared Error (MSE), and Root Mean Squared Error (RMSE). SHapley Additive exPlanations (SHAP) analysis was applied to identify key features and ensure model interpretability. All three models achieved prediction accuracies above 85%. SHAP analysis revealed that PM10 levels, air

quality type, atmospheric pressure, and wind speed were among the most influential factors, highlighting the combined impact of meteorological conditions and anthropogenic emissions on particulate pollution in Delhi, India. The findings demonstrate that machine learning–based models can serve as effective tools for short-term PM2.5 forecasting, enabling timely interventions, informed policy decisions, and data-driven urban health management. Future research should focus on incorporating multi-year datasets, satellite-derived aerosol products, and hybrid deep learning architectures to enhance long-term reliability and real-world applicability.

Keywords: Air Quality Prediction; Machine Learning (ML); PM 2.5; Predictive Modeling

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SORT SMART: THE POWER OF WASTE SEGREGATION

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ABSTRACT
Waste management has become a critical environmental and public health issue due to rapid urbanization, industrial growth, and population expansion. Improper disposal of solid waste leads to pollution, greenhouse gas emissions, soil and water contamination and severe health hazards. To address these challenges, an integrated and sustainable waste management approach is essential. Modern waste management systems emphasize waste minimization at the source, segregation, recycling, composting of organic materials, energy recovery technologies, and safe scientific disposal of non-recyclable residues. Additionally, emerging innovations such as IoT- based waste tracking, smart bins, decentralized waste processing systems, and circular economy models are enhancing efficiency and resource recovery. Public participation, policy enforcement, and awareness programs play a crucial role in ensuring effective implementation. A comprehensive waste management strategy not only reduces environmental impacts but also converts waste into valuable resources, promoting sustainable development and cleaner urban living.

Keywords: Waste Management, Solid Waste Disposal, Recycling, Composting, Circular Economy, Waste Segregation, Resource Recovery, Waste-to-Energy, Environmental Sustainability, Pollution Control, Municipal Solid Waste, Sustainable Development.

SMART GRIDS AND RENEWABLE ENERGY INTEGRATION

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ABSTRACT
The increasing global energy demand and the depletion of conventional energy resources have accelerated the need for a more efficient, reliable, and sustainable power system. Smart Grid technology has emerged as a modern solution that combines electrical engineering, renewable energy integration, automation, and communication networks to revolutionize the existing power infrastructure. Unlike traditional power grids that operate in a unidirectional flow of electricity, Smart Grids facilitate bidirectional communication between utilities and consumers, enabling real-time monitoring, control, and optimization of energy usage. This intelligent system not only enhances energy efficiency but also ensures better utilization of renewable energy sources such as solar, wind, and hydro power. However, the implementation of Smart Grids faces several challenges, including grid instability due to fluctuating renewable inputs, high installation and maintenance costs, cybersecurity vulnerabilities, and the need for advanced data management systems. To address these challenges, our research focuses on developing an integrated Smart Grid model using IoT-based sensors, Artificial Intelligence (AI), and Machine Learning (ML) algorithms. These technologies enable accurate prediction of energy demand, fault detection, automated load balancing, and self-healing capabilities. The proposed system can adapt to variations in renewable energy generation, ensuring uninterrupted and stable power supply even during peak demand conditions. Furthermore, the integration of big data analytics will allow continuous evaluation of grid performance, while blockchain technology can ensure secure and transparent energy transactions between producers and consumers. The use of decentralized control systems reduces dependency on centralized power plants, promoting the concept of microgrids and community-based renewable energy systems. By implementing this intelligent grid model, we can achieve higher energy efficiency, reduced carbon emissions, and improved reliability of power delivery. This research aims to create a future-ready power system that aligns with global sustainability goals while enhancing the overall performance and resilience of the electrical network

Keywords: Smart Grid; Renewable Energy; Artificial Intelligence; Internet of Things; Machine Learning; Blockchain; Power Distribution; Sustainability.

POLLUTION: A MAJOR BARRIER TO SUSTAINABLE DEVELOPMENT

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ABSTRACT

Pollution is one of the most critical environmental issues affecting life on Earth. It refers to the introduction of harmful substances or contaminants into the natural environment, causing adverse effects on living organisms and the ecosystem. Rapid industrialization, urbanization, deforestation, and technological advancement have accelerated pollution levels globally. There are several major types of pollution, including air, water, soil, noise, and thermal pollution. Air pollution results from the release of toxic gases and particulates from vehicles, industries, and the burning of fossil fuels, leading to respiratory diseases and global warming. Water pollution occurs when harmful chemicals and waste materials contaminate water bodies, affecting aquatic life and human health. Soil pollution arises from the excessive use of pesticides, fertilizers, and improper waste disposal, reducing soil fertility. Noise pollution, caused by traffic, industrial operations, and urban activities, affects human mental health and wildlife behaviour. Thermal pollution is the rise in water temperature due to industrial discharges, disturbing aquatic ecosystems. In conclusion, pollution poses a serious threat to the balance of nature and human well-being. Effective waste management, renewable energy use, afforestation, and strict environmental regulations are essential to control pollution and ensure a sustainable future.

Keywords: Pollution, Environment, Air Pollution, Water Pollution, Soil Pollution, Noise Pollution, Thermal Pollution, Industrialization, Urbanization, Ecosystem, Contamination, Global Warming, Health Hazards, Waste Management, Sustainability.

NOVEL 1,3,4-OXADIAZOLE CARBAMOTHIOATES AS ANTICONVULSANT AGENTS: FROM SYNTHESIS AND MOLECULAR DOCKING TO ELECTROPHYSIOLOGICAL VALIDATION

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ABSTRACT

In present work, a series of novel structural hybrids of 1,3,4-oxadiazole and carbamothioate was designed by chemical modification of 2-(4-isobutylphenyl) propanoic acid. Target compounds (7a-f) were synthesized in significant yields (84-88%) by coupling compound (4) with different electrophiles under different reaction conditions. The structures of oxadiazole based carbamothionate derivatives were confirmed by spectroscopic (FTIR, ^{1}HNMR, ^{13}CNMR) and physiochemical methods. During *in-vivo* experimentation, all synthesized compounds were tested through 6 Hz (32 mA) and PTZ (80 mg/kg) mouse seizure models. The 7b and 7c showed significant outcomes ($P<0.05$) in terms of seizure severity, protection and mortality. The behavioural outcomes of PTZ tests were further strengthened with video electroencephalogram (vEEG) findings in which EEGs were analyzed for epileptic spikes to understand the impact of 7b and 7c treatment on these ictal activities. The 7b was found most efficient in reducing the seizure spiking activity in brains of PTZ-treated mice while both 7b and 7c significantly reduced overall PTZ-induced seizure severity. The molecular docking studies also predicted the BBB permeability, reduced binding energies and good compound interaction with $GABA_A$ receptors and SV2A protein. Therefore, the observed pharmacological outcomes might be attributed to the $GABA_A$ agonistic and SV2A modulating potential of these oxadiazole-carbamothioate hybrid compounds.

Keywords: Epilepsy, 6 Hz, PTZ, 1,3,4-oxadiazole, carbamothioate, Electroencephalogram, Seizure

INTELLIGENT HIGHWAY LANE CHANGES: ENHANCING SAFETY AND COMFORT THROUGH PREDICTIVE SENSOR FUSION AND TRAJECTORY OPTIMIZATION

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ABSTRACT

One of the most important uses of autonomous vehicles is highway driving, specifically when it comes to the complicated problem of changing lanes in busy, complex, and rapidly changing environments. Lane changes require immediate decisions to be made while ensuring safety and considering the overall efficiency and comfort of the passengers. To address all these factors, we propose an integrated approach which merges cutting-edge sensor fusion technology with optimal trajectory planning. By using internal and external sensors, the proposed framework can track and understand the environment in all surroundings while emphasizing critical object detection. Through focused sensor fusion, the data from disparate sources can be integrated, which improves complex scenario perception reliability. For path generation, we use the Frenet coordinates system with jerk optimized planning, which creates smooth, feasible, and collision-free paths that align with road curvature. The approach taken reduces sharp turns, thus ensuring the comfort of passengers. The framework has been validated through a highway lane-change simulation platform that exemplifies a variety of traffic conditions. Results show that automated lane changes successful executed within the time headway parameters and adapted appropriately to the dynamic system changes. When sensor fusion predictive trajectory planning was employed, more robust and safe decision making was executed. These results contrast to the sensor fusion predictive trajectory planning results. This results indicate more robust and safe decision making when predictive sensor fusion is used to guide automated lane changes. This autonomous driving study combines perception with trajectory optimization, paving the way for intelligent lane-changing algorithms and more autonomous vehicles that are safe and reliable for highway travel.

Keywords: autonomous vehicles, lane change, sensor fusion, trajectory planning, highway driving

DANCE AS ATHLETIC PERFORMANCE: THE ROLE OF FUNCTIONAL FOOD IN ENHANCING DANCER HEALTH AND NUTRITION

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ABSTRACT

Dance, while often celebrated as a performing art, also demands the physical rigor and discipline of a high-performance sport. Dancers endure intense training schedules, long rehearsals, and physically demanding performances that require strength, endurance, flexibility, coordination, and mental focus. As with athletes in any sport, proper nutrition plays a critical role in supporting the physical and cognitive demands of dancers. In recent years, the integration of functional foods into dancers' diets has gained increased attention for its potential to enhance performance, support recovery, and prevent injuries. This review explores the dual nature of dance—as both an expressive art form and a physically intensive sport—and highlights the unique nutritional requirements of dancers. Unlike many traditional athletes, dancers often face pressures related to body image and aesthetic expectations, which can influence their dietary behaviors and risk of nutrient deficiencies. Functional foods—such as those rich in antioxidants, omega-3 fatty acids, probiotics, and bioactive compounds—offer targeted benefits, including improved joint health, enhanced muscle recovery, reduced inflammation, and better gut health. Such foods can be particularly beneficial for dancers striving to maintain peak physical condition without compromising their long-term health. By examining current research on functional nutrition in the context of dance, this paper aims to provide practical insights for dancers, coaches, and nutritionists. It underscores the importance of evidence-based dietary strategies that support both the artistic and athletic dimensions of dance, contributing to the overall performance, resilience, and well-being of dancers across various styles and levels of expertise.

Keywords: dance, functional food, sports nutrition, dancer health, performance enhancement.

PROCESS INTENSIFICATION BY CONTINUOUS FLOW MICROREACTOR FOR THE SYNTHESIS OF SNO_2 NANOPARTICLES USING NATURAL REDUCING AGENT

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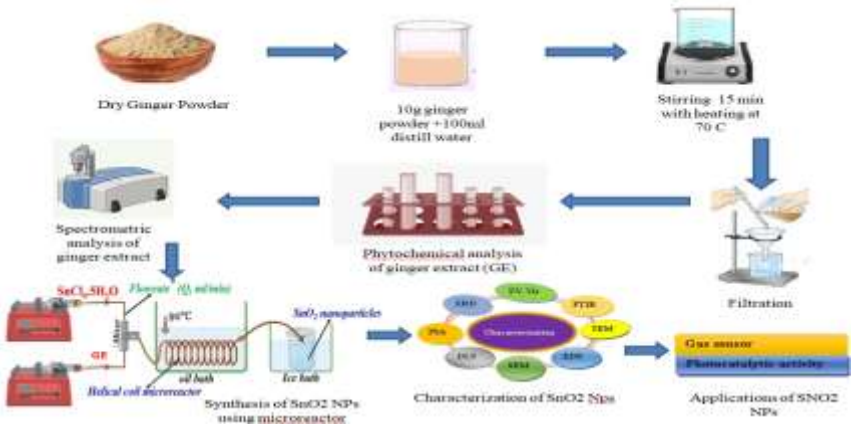
ABSTRACT
Water pollution is one of the major challenges faced now a days due to lot of carcinogenic and hazardous chemicals released by various dyes. Enhancement in the capabilities such as heat transfer, reaction kinetics, scalability, yields etc were observed in the chemical products synthesized by continuous flow microreactor, as it utilizes the synthesis technique of flow chemistry. Continuous flow microreactors are more advantageous than conventional batch reactors, as reaction takes place in the microchannel and also continuously. The present study highlights the synthesis of SnO_2 nanoparticles in a continuous flow microreactor using natural reducing agent. SnO_2 is a n – type semiconductor and till now exploration has not conducted on synthesis of SnO_2 nanoparticles in a continuous flow microreactor using natural reducing agents, which acts also as capping agent. Natural reducing agents are highly proficient sources of flavonoids, phenols etc which do not produce any hazardous chemicals that damage ecosystem during the synthesis of SnO_2 nanoparticles. Characterization is done by X – Ray Diffraction, Fourier Transform Infrared Spectroscopy, TEM and SEM.

Keywords: *Microreactor, reaction kinetics, nanoparticles, capping agent, semiconductor*

GRAPHICAL ABSTRACT



THE ROLE OF EMOTIONAL INTELLIGENCE TRAINING IN MANAGERIAL EFFECTIVENESS

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ABSTRACT

Purpose: This study seeks to explore the role of emotional intelligence (EI) training in boosting managerial effectiveness within organizations. It aims to clarify the connection between EI skills and managerial outcomes, including decision-making, team leadership, and adaptability. Methodology: The research relies on secondary data analysis from peer-reviewed journals, organizational case studies, and meta-analytical reports published in the last ten years. A systematic review method was employed to compile findings on the implementation and results of EI training programs. Findings: The review reveals that managers who participate in EI training show enhanced communication, better conflict management skills, and increased motivation among their team members. Organizations that incorporate EI-focused interventions experience noticeable improvements in leadership performance and employee engagement. Implications: The findings highlight the importance of institutionalizing EI training as a strategic tool for leadership development rather than treating it as a secondary HR initiative. It provides valuable insights for academics, HR professionals, and policymakers aiming to improve managerial skills through evidence-based emotional intelligence frameworks.

Keywords: Emotional Intelligence, Managerial Training, Leadership Development, Secondary Data, Organizational Effectiveness

SUSTAINABLE RETAIL ENVIRONMENTS: A DESIGN-BASED EXPLORATION OF ZERO-WASTE GROCERY STORES

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ABSTRACT

Grocery stores, as a common form of retail chain, play a pivotal role in shaping consumer behavior and environmental responsibility. The idea of a sustainable grocery store extends beyond the traditional shopping experience to create an ethical, economical, and eco-friendly space where waste materials are minimized, reused, and transformed into resources. These stores aim to eliminate plastic packaging by promoting alternatives such as refill stations and encouraging customers to bring their own reusable containers. The primary goal is to reduce dependency on single-use plastics while promoting the guiding principles of the 3Rs: Reduce, Reuse, and Recycle. This research adopts a design-based methodology to conceptualize and evaluate sustainable grocery stores. Site observations, spatial analysis, and case studies of existing zero-waste and green stores are employed to identify design elements that enhance user experience, operational efficiency, and environmental performance. The methodology focuses on how interior layouts, material selection, circulation patterns, and display systems can be optimized to encourage sustainable practices. Attention is also given to the integration of renewable energy systems, natural lighting, and ventilation strategies to further reduce ecological footprints.Findings reveal that well-planned design solutions not only facilitate resource conservation and energy efficiency but also create environments that positively influence customer participation in sustainability. By prioritizing non-toxic, recyclable, and locally sourced materials, these stores foster trust and engagement within communities. Moreover, aligning with the United Nations Sustainable Development Goals (SDGs), sustainable grocery stores serve as prototypes for environmentally responsible retailing, offering a replicable model that balances ecological impact with commercial viability.

Keywords: Sustainable design, zero waste grocery store, 3Rs (Reduce, Reuse, Recycle), green building, resource conservation, user-centered design, renewable energy integration.

DESIGN AND DEVELOPMENT OF ORAL CONTROLLED RELEASE SYSTEMS FOR SUSTAINED DRUG DELIVERY

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ABSTRACT
Oral controlled release medication delivery systems are made to minimize dosage frequency and adverse effects while maintaining therapeutic drug concentrations in the systemic circulation for prolonged periods of time. Drug physicochemical characteristics, biopharmaceutical considerations, polymer selection, and formulation techniques are all carefully taken into account during the development of such systems. To produce prolonged release by regulating the rate of drug dissolution, diffusion, or erosion, a variety of technologies are used, such as hydrophilic matrix systems, osmotic pumps, reservoir systems, and gastroretentive dosage forms. The possibilities for accurate release modulation have been further increased by developments in polymer chemistry and contemporary processing methods like hot-melt extrusion and 3D printing. Controlled release formulations are very useful for managing chronic diseases because they improve therapeutic efficacy, decrease variations in plasma drug levels, and improve patient compliance. An overview of the fundamentals, design factors, assessment criteria, and most current developments in oral controlled release systems for long-term medication delivery are given in this article.
Keywords: Matrix system, Controlled release formulation, Gastroretentive system, Oral controlled release, Design factor

A SECURE AND RESILIENT EDGE-BLOCK-CHAIN NEURAL NETWORK SYSTEM FOR INDUSTRIAL POLLUTION MONITORING UNDER GPRS OUTAGES

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ABSTRACT

Industry-scale pollution monitoring in steel manufacturing is hindered by unreliable GPRS communication, frequently resulting in loss of emission data and compliance risks. In response, this work presents a secure, resilient architecture employing edge controllers for local storage of encrypted stack emission metrics, including SPM, SO_2, CO, flow, and temperature. Data is encrypted with AES prior to transmission, ensuring privacy and integrity. Block-chain-based data validation implements immutability and auditability via chained cryptographic hashes. Upon network restoration, verified records are transmitted securely to a central server. Neural network models are deployed to process stored and live data, enabling predictive analytics and anomaly detection for early intervention. Field deployment confirms the elimination of data loss during outages, enhanced security, and proactive compliance management. The integrated solution transforms traditional pollution monitoring into an adaptive, intelligent system, supporting data-driven optimization and regulatory assurance, and is broadly applicable across industrial environmental monitoring scenarios.

Keywords: Steel industry; pollution monitoring; edge computing; data encryption; block-chain; neural networks; GPRS outage; anomaly detection; compliance

SYNTHESIS AND CHARACTERIZATION OF LI_2ZNSNO_4 BY SOL-GEL METHOD AND FIRST PRINCIPALS STUDY

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ABSTRACT

The quaternary $I_2-II-IV-O_4$ semiconductors, like Li_2ZnSnO_4, hold promise as a solar absorber for photovoltaic and optoelectronic applications. In this work, we focused on (a) a theoretical study and (b) an experimental investigation of Li_2ZnSnO_4 composition. In the theoretical part, the structural, electrical, and optical properties of Li_2ZnSnO_4 are analyzed using a first-principles approach within the framework of density functional theory (DFT), as implemented in the CASTEP code. The mechanical stability of the compound is verified using the Born-Huang criteria, with the estimated elastic constants indicating that Li_2ZnSnO_4 is mechanically soft, malleable, and isotropic. Electronic band structure analysis reveals that the monoclinic phase of Li_2ZnSnO_4 exhibits a direct electronic transition with a bandgap of 2.011 eV. Optical properties such as the dielectric function, absorption, reflectivity, refractive index, optical conductivity, and loss function are also studied. The absorption coefficient of Li_2ZnSnO_4 is found in the order of $\sim 10^5$ cm^{-1} in the UV region. Its high absorption, low reflectivity, and optical anisotropy make it an excellent candidate for waveguides, dielectric condensers, optical displays, and UV-based photocatalysts. In the experimental part, we synthesized Li_2ZnSnO_4 by sol-gel method and studied its structural and morphological properties using TG-DTA, XRD, SEM, FTIR, and UV-Vis optical properties by spectrophotometer. The thermal behavior of the Li_2ZnSnO_4 compound was examined using DG-DTA to determine the optimal calcination temperature for stabilizing the compound. XRD results show that the compound crystallizes in a monoclinic phase with lattice parameters of a = 4.741 Å, b = 7.984 Å, c = 9.538 Å, β = 84.64°, and a cell volume of 359.472 $Å^3$. The average crystallite size of the synthesized Li_2ZnSnO_4 crystallites, calculated using Scherrer's formula, is 35.33 nm. SEM images reveal grains are interconnected and irregular in shape and size. FTIR analysis confirms the formation of the compound, with strong stretching vibrations corresponding to Zn-O and Sn-O bonds, along with characteristic C-H and C=C bonds. UV-Vis spectroscopy indicates high transmittance and reflectance, with an optical direct bandgap of 1.801 eV. Moreover, optical parameters such as the refractive index, absorption coefficient, extinction constant, and dielectric functions (both real and imaginary components) are analyzed as a function of photon energy. Overall, the experimental and theoretical findings of Li_2ZnSnO_4 manifest the suitability of optical and photocatalytic applications.

Keywords: Li_2ZnSnO_4; Sol-Gel Method; Structural Properties; Optical Properties, morphological properties, XRD

A COMPREHENSIVE INVESTIGATION ON EGGSHELL POWDER AS NATURAL ADSORBENT FOR METHYL ORANGE DYE REMOVAL: A STUDY OF KINETICS, ISOTHERM AND THERMODYNAMICS

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ABSTRACT

The discharge of synthetic dyes from textile and industrial effluents into aquatic ecosystems poses severe environmental and health hazards, necessitating the development of sustainable dye removal strategies. This study aims to investigate the feasibility of using eggshell powder (ESP), a cost-effective and eco-friendly waste material, as a natural adsorbent for the removal of methyl orange (MO), a commonly used anionic azo dye, from aqueous media. The study explores the adsorption process in terms of kinetics, isotherms, thermodynamics, and mechanistic pathways. ESP was prepared through washing, drying, grinding, and sieving processes, and characterized using SEM, EDX, FTIR, and pHZPC analysis to understand its surface morphology, elemental compositions, and functional groups. Batch adsorption experiments were conducted to optimize parameters, including pH, initial dye concentration, contact time, ESP dosage, and temperature. The optimal dye removal (73.86%) and adsorption capacity 4.61665 mg/g were achieved at pH 2.0, 5 ppm dye concentration, 0.4 g/L ESP dosage, 30 °C, and 65 minutes contact time. Kinetic studies revealed that the adsorption followed the Lagergren pseudo-first-order model ($R^2 = 0.9554$), indicating a physisorption-driven process. Isotherm analysis showed better correlation with the Freundlich model, suggesting multilayer adsorption on heterogeneous surfaces. Thermodynamic analysis revealed a negative enthalpy change ($\Delta H = -98.61$ kJ/mol), supporting an exothermic and spontaneous chemisorption mechanism. The proposed adsorption mechanism involves both electrostatic attraction and π–π interactions between MO and the ESP surface. This study demonstrates the promising potential of unmodified eggshell powder as a sustainable and efficient adsorbent for dye-contaminated water.

INFLUENCE OF CLIMATIC FACTORS AND CROPPING SYSTEM ON THE AGRONOMIC CHARACTERISTICS OF OLIVES (OLEA EUROPAEA *L.*) OF THE *MOROCCAN PICHOLINE* VARIETY CULTIVATED IN THE OLIVE-GROWING REGIONS OF MOROCCO

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ABSTRACT

The Moroccan olive oil sector is distinguished by a great varietal diversity, dominated at 96% by the *Moroccan Picholine* variety. This study aims to agronomically characterize the olives of this variety cultivated in two large regions: the north, including Tetouan, Chaouan and Ouazzane, and the center, encompassing Settat, Kelaa of Sraghna and Marrakech. In each site, five trees were sampled, at a rate of 40 fruits per tree. The objective of this work is to study the influence of cropping system (irrigated/rainfed) and climatic factors on olive tree pomology in different sites in Morocco. Eight quantitative traits concerning fruit weight (FM), stone mass (CM), fruit length (FL), fruit width (FW), fruit length/width (FL/FW), stone length/width (CL/CW) and Pulp/stone ratio (PC) as well as an indirect estimation of oil content via the percentage of pulp (PF). The results reveal significant variations across sites: the size and productive potential of olives differ progressively, while shape-related characteristics play a secondary role. Olives are larger in the irrigated sites Kelaa of Sraghna, Settat, and Marrakech, and smaller in the rain-fed sites of Ouazzane, Chaouan, and Tetouan. These variations are mainly explained by environmental conditions, including climatic factors and the cropping system. Irrigated systems produce larger, oil-rich olives than rainfed systems.. During the 2023-2024 agricultural campaign.

Keywords: Olive tree, *Moroccan Picholine*, north-center, cropping system, agronomical parameters.

STRUCTURAL AND OPTICAL PROPERTIES OF BARIUM DOPED LANTHANUM MOLYBDATE

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ABSTRACT

Lanthanum based scheelite-type oxides have recently attracted attention for their luminescence and thermal conduction properties. These studies mainly focused on the undoped $La_2Mo_3O_{12}$ for thermal conductivity and lanthanide doped (Eu, Dy, Sm etc.) $La_2Mo_3O_{12}$ for luminescence applications of the material. In this study, Ba doped (≤5%) $La_2Mo_3O_{12}$ was prepared using a co-precipitation and calcination approach. The structure of the samples was studied by XRD and SEM, and UV-Vis spectroscopy and photoluminescence measurements were carried out to investigate the optical properties. XRD results showed that single phase Ba doped samples could be synthesised with a simple approach. The samples had a monoclinic structure with space group C2/c. SEM results showed that the particle size was unaffected by the level of Ba doping. SEM micrographs showed that the particles had sphere-like irregular shapes with ~1 μm diameter. SEM-EDS results revealed the homogeneous distribution of La, Mo, Ba and O elements in the samples. Optical band gap, E_g values were calculated from the UV-vis spectroscopy data using Tauc relationship given by $(\alpha h\nu)^n = A(h\nu-E_g)$. The results showed that E_g was 3.03-3.32 eV for the samples. The emission spectra of the Ba doped samples were recorded under the excitation at 352 nm. A prominent emission band at ~530 nm was observed for all the samples.

Keywords: $La_2Mo_3O_{12}$, Ba doping, structural properties, optical properties

OTOMOTİV SEKTÖRÜNDE KULLANIMA UYGUN LAZER TRANSPARANLIK ÖZELLİĞİNE SAHİP, HİDROLİZ DAYANIMLI PA6.6 KOMPOZİT MALZEMELERİN GELİŞTİRİLMESİ

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ÖZET

PA 6.6 (Poliamid 6.6), yüksek mekanik dayanım, ısıya direnç, boyutsal kararlılık ve aşınma direnci gibi üstün özellikleri sayesinde otomotiv, elektrik-elektronik, tekstil ve ambalaj sektörlerinde yaygın olarak kullanılan bir mühendislik termoplastiğidir. Ancak, PA6.6 malzemeleri uzun süreli nem veya suya maruz kaldığında hidrolitik olarak bozunabilir. Bu durum, özellikle dış ortam koşullarına açık otomotiv parçalarında mekanik performansın düşmesine yol açmaktadır. Bu nedenle, hidroliz dayanımı geliştirilmiş yeni formülasyonların oluşturulması, malzemenin kullanım ömrü ve güvenilirliği açısından kritik önem taşımaktadır. Bunun yanında, Lazer kaynaklama, yüksek hassasiyetli, hızlı ve temiz bir birleştirme yöntemi olarak otomotiv üretiminde giderek daha fazla tercih edilmektedir. Bu yöntemin başarılı olabilmesi için, kaynaklanacak malzemelerin lazer ışığına karşı belirli bir transparanlık ve soğurma dengesi göstermesi gerekmektedir. Bu çalışmada geliştirilen PA6.6 bazlı malzeme, bu optik özellikleri optimize edecek katkı sistemleri ile tasarlanmıştır. Böylece, siyah renkte olan malzemenin lazer ışığını belirli dalga boylarında geçirerek kaynaklanabilirlik özelliğini koruması beklenmiştir. Çalışmada, otomotiv endüstrisinde lazer kaynaklama prosesine uygun, cam elyaf dolgulu ve hidroliz dayanımlı siyah PA 6.6 kompozit malzeme geliştirilmesi hedeflenmiştir. Hazırlanan karışımlar, çift vidalı ekstrüder kullanılarak eriyikten karıştırma yöntemi ile hazırlandıktan sonra fitil formunda üretilmiştir. Ekstrüzyon sonrası elde edilen polimer fitiller, granülatör yardımıyla granül hale getirilmiştir. Bu granüller, ISO 527 standardına uygun çekme plakaları ve darbe plakaları halinde preslenerek test numuneleri hazırlanmıştır. Üretilen numuneler üzerinde mekanik testlerin yanı sıra lazer geçirgenlik analizleri yapılmıştır. Lazer transparanlık testleri ile farklı plaka kalınlıklarında (0,8 mm, 1,6 mm ve 3,2 mm) üretilen malzemenin lazer geçirgenliği yüzdesi belirlenmiştir. Üretilen malzemelerde, hidroliz testi yapılmış ve test sonrası malzemelerin mekanik özelliklerinin; çekme ve darbe testlerinde %50 ve üzerinde korunduğu gözlemlenmiştir. Aynı zamanda lazer geçirgenlik değerinin %20 üzerinde olduğu test edilmiştir. Bu çalışma, otomotiv endüstrisinde hem fonksiyonel hem de estetik gereksinimleri karşılayabilecek, enerji verimliliği yüksek, çevre dostu ve uzun ömürlü malzeme çözümleri sunmaktadır.

Anahtar Kelimeler: Poliamid 6.6, Mekanik Özellikler, Lazer Geçirgenlik, Hidroliz Dayanımı

DEVELOPMENT OF HYDROLYSIS RESISTANT PA6.6 COMPOSITE MATERIALS WITH LASER TRANSPARENCY SUITABLE FOR USE IN THE AUTOMOTIVE INDUSTRY

ABSTRACT

Polyamide 6.6 (PA66) is an engineering thermoplastic widely used in the automotive, electrical-electronic, textile, and packaging industries due to its superior properties such as high mechanical strength, heat resistance, dimensional stability, and wear resistance. However, PA66 materials can undergo hydrolytic degradation when exposed to moisture or water for extended periods. This phenomenon leads to a decline in mechanical performance, particularly in automotive components exposed to outdoor environmental conditions. Therefore, developing new formulations with improved hydrolysis resistance is of critical importance in terms of the material's service life and reliability. In addition, laser transmittance has become an increasingly preferred joining method in automotive manufacturing due to its high precision, speed, and cleanliness. For successful laser transmittance, the materials to be joined must exhibit an appropriate balance of laser transparency and absorption. In this study, a PA66-based material was formulated with additive systems optimized for these optical properties, enabling the black-colored material to maintain weldability by transmitting laser light at specific wavelengths. The study aimed to develop a glass fiber reinforced, hydrolysis-resistant, and laser-transparency black PA66 composite suitable for the laser transmittance process in the automotive industry. The prepared mixtures were compounded using a twin-screw extruder through a melt-blending process and subsequently pelletized via a granulator. The resulting granules were compression molded into tensile and impact specimens in accordance with ISO 527 standards. The samples produced were subjected to mechanical tests as well as laser transmittance analyses. Laser transparency tests were conducted on plates of different thicknesses (0.8 mm, 1.6 mm, and 3.2 mm) to determine the percentage of laser transmittance. After hydrolysis testing, the mechanical properties of the materials were retained by 50% or more in tensile and impact performance, while the laser transmittance value exceeded 20%. This study presents an energy-efficient, environmentally friendly, and durable material solution that meets both the functional and aesthetic requirements of the automotive industry.

Keywords: Polyamide 6.6, Mechanical Properties, Laser Transmittance, Hydrolysis Resistance

ELEKTRİK ELEKTRONİK SEKTÖRÜNDE KULLANIMA UYGUN PBT/rPET HARMANLARININ ÖZEL RENKLERDE ELDESİ

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ÖZET

Günümüzde hızla artan plastik tüketimi ve buna bağlı olarak ortaya çıkan atık miktarı, sürdürülebilir üretim anlayışını endüstriyel süreçlerin vazgeçilmez bir parçası haline getirmiştir. Özellikle elektrik-elektronik sektörü gibi yüksek performans gerektiren alanlarda, çevresel etkileri azaltırken ürün kalitesini koruyacak çözümler geliştirmek büyük önem taşımaktadır. Bu bağlamda, geri dönüştürülmüş polimerlerin mühendislik uygulamalarında yeniden değerlendirilmesi hem kaynak verimliliğini artırmakta hem de karbon ayak izinin azaltılmasına katkı sağlamaktadır. Polibütilen tereftalat (PBT) ve geri dönüştürülmüş polietilen tereftalat (rPET) harmanları, mekanik dayanım, ısıl kararlılık ve boyutsal kararlılık gibi özellikleriyle sürdürülebilir mühendislik plastikleri arasında öne çıkmaktadır. Bu çalışma kapsamında, elektrik-elektronik uygulamalarında kullanılmak üzere PBT/rPET harmanlarının geliştirilmesi ve bu harmanların RAL renk hedeflerine uygun biçimde üretilmesi amaçlanmıştır. Böylece, geri dönüştürülmüş malzemelerin yüksek katma değerli uygulamalarda kullanılabilirliği artırılarak hem çevresel hem de ekonomik sürdürülebilirliğe katkı sunulması hedeflenmiştir. Ral kartelası, boya, kaplama ve plastikler için renkleri tanımlayan bir Avrupa renk eşleştirme sistemidir. Bu çalışmada elde edilecek ürünlerde kontrol numunesiyle benzer, yüksek mekanik özelliklerde siyah, beyaz ve gri renkli elektrik-elektronik sektöründe kullanıma uygun parçalarının üretimi yapılmıştır. Bunun için, renkli, PBT ve rPET kompozitleri, çift vidalı ekstrüderde eriyikten karıştırma yöntemiyle üretilmiştir. Üretilen örneklere yönelik mekanik testler ve renk kontrolü, enjeksiyon makinesinde basılmış test plakalarına uygulanmıştır. Üretilen malzemelerin karakterizasyonu için çekme testi, basma ve bükülme, darbe dayanımı testleri, yük altında eğilme sıcaklığı tayini, erime sıcaklığı tayini ve renk kontrolü yapılmıştır. Çalışmada, RAL 7035, RAL 9005 ve RAL 9016 renk standardına göre ΔE renk değişim değerinin <1 olması hedeflenmiştir. Çalışma sonucunda kontrol numunesine göre mekanik özellikler etkilenmeden istenilen siyah, beyaz ve gri renge ulaşılmıştır. Renk testleri sonucunda ΔE değişimi <1 olarak tespit edilmiştir. Hem mekanik özellikler hem de renk standardı açısından hedeflenen kriterler sağlanmıştır. Geliştirilen PBT/rPET harmanları, elektrik-elektronik endüstrisinin hem fonksiyonel hem de estetik gereksinimlerini karşılayabilecek, çevreye duyarlı ve uzun ömürlü malzeme çözümleri sunmaktadır.

Anahtar kelimeler: PBT, rPET, RAL standardı, Elektrik-Elektronik Sektörü

PRODUCTION OF CUSTOM-COLORED PBT/rPET BLENDS SUITABLE FOR ELECTRICAL AND ELECTRONIC APPLICATIONS

ABSTRACT

In recent years, the increase in plastic consumption and the consequent growth in waste generation have rendered sustainable production an essential component of industrial processes. Particularly in high-performance sectors such as electrical and electronic industries, the development of solutions that mitigate environmental impact while maintaining product quality has become a critical priority. In this regard, the reuse of recycled polymers in engineering applications not only enhances resource efficiency but also contributes to the reduction of the overall carbon footprint. Among sustainable engineering plastics, polybutylene terephthalate (PBT) and recycled polyethylene terephthalate (rPET) blends have attracted considerable attention due to their suitable mechanical strength, thermal stability, and dimensional integrity. The present study aims to develop PBT/rPET blends suitable for electrical and electronic applications and to produce these blends in compliance with RAL color standards. By promoting the incorporation of recycled materials into high value-added applications, this study seeks to contribute to both environmental and economic sustainability. The RAL color chart is widely used across Europe, serves as a standardized framework for color matching in paints, coatings, and plastics. In this study, black, white, and gray components exhibiting high mechanical performance and comparable color characteristics to the control sample were produced for use in the electrical and electronic sector. Subsequently, colored PBT and rPET blends were prepared via melt blending in a twin-screw extruder. Mechanical testing and color evaluation were performed on test plaques molded by injection molding. Characterization of the produced materials included tensile, compression, and flexural strength tests, impact tests, heat deflection temperature (HDT) determination, melting temperature analysis, and color measurement. According to RAL 7035, RAL 9005, and RAL 9016 color standards, a ΔE color difference value below 1 was targeted. The target black, white, and gray colors were achieved without compromising the mechanical performance relative to the control sample. Also, color measurements confirmed that ΔE values remained below 1. Both the mechanical and color performance criteria were successfully met. The developed PBT/rPET blends consequently present environmentally responsible and durable material alternatives capable of meeting the functional and aesthetic requirements of the electrical and electronic industry.

Keywords: PBT, rPET, RAL standard, Elektric and Electronics Industry

INTEGRATION OF RESTORATIVE DESIGN FEATURES IN RESORT ARCHITECTURE IN ABUJA, NIGERIA

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ABSTRACT

In an era marked by heightened stress and environmental degradation, restorative design is gaining prominence as a sustainable approach to architectural development. This study examines how biophilic interventions and spatial configuration strategies influence restorative experiences within resort environments in Abuja, Nigeria. Employing a quantitative research design, data were collected from a diverse sample of resort users through digital survey platforms. Descriptive and inferential analyses, including correlation, multiple regression and exploratory factor analysis (PCA with Varimax rotation), were conducted to assess relationships among Restorative Principles Evaluation (RPE), Biophilic Interventions (BIRE), and Prospect–Refuge Restorative (PRR) constructs. Findings indicate strong positive correlations between RPE and both BIRE ($r = 0.763$, $p < 0.01$) and PRR ($r = 0.632$, $p < 0.01$), with BIRE showing a stronger predictive influence on restorative perception ($\beta = 0.659$, $p < 0.001$). The model explained 59% of the total variance ($R^2 = 0.590$), confirming that the integration of daylight, vegetation, water elements and natural materials, along with spatial attributes such as legibility, prospect and refuge, significantly enhances user well-being. Demographic variations also moderated restorative appraisals, underscoring user diversity in design response. The study advances a sustainable, context-sensitive framework for resort architecture in Nigeria, advocating for restorative design strategies that align ecological sensitivity with human psychological needs.

TELEPHARMACY AND DIGITAL HEALTH ECONOMICS.

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ABSTRACT
Telepharmacy, the delivery of pharmaceutical care through digital platforms, has emerged as a cost-effective model for improving healthcare access, especially in rural and underserved regions. By integrating digital health technologies such as electronic prescriptions, teleconsultations, mobile health apps, and AI-based medication management, telepharmacy reduces geographical barriers and optimizes resource utilization. From an economic perspective, it minimizes the need for physical infrastructure, lowers travel costs for patients, and decreases hospital readmissions by improving adherence and monitoring. Furthermore, digital health economics highlights the balance between upfront technology investment and long-term savings in healthcare expenditure. While challenges such as regulatory barriers, digital literacy, and data security remain, telepharmacy demonstrates significant potential in enhancing healthcare efficiency, affordability, and equity. Its adoption represents a paradigm shift towards sustainable, patient-centered healthcare systems.
Keyword: Telepharmacy Digital health Health eeconomic, CCost-effectivenes, Remote patient care, Medication adherence, Prescriptio, Mobile health (mHealth),Healthcare accessibility,Rural healthcare,Cost mminimizatio, Digital health equity,Patient-centered care,Pharmacoeconomic.

MODERATING ROLE OF SELF-CONCEPT CLARITY BETWEEN CELEBRITY WORSHIP AND DESIRE FOR FAME AMONG YOUNG ADULTS

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ABSTRACT

The present study aimed to investigate the moderating role of self-concept clarity between celebrity worship and desire for fame among young adults. For this purpose, a sample of (*N*=300) young adults was taken from Rawalpindi and Islamabad. Data was collected from the sample via a demographic form and three questionnaires, each for one study variable. Celebrity worship was studied using the Celebrity Worship Scale CWS (McCutcheon et al., 2002), desire for fame was studied using the Desire for Fame Scale (Gountas et al., 2012), and self-concept clarity was measured using the Self-Concept Clarity Scale (Campbell et al., 1996). Correlational, regression, and moderation analyses were performed to explore the relationship between the study variables. Additionally, *t*-tests and ANOVA were applied to study the effect of demographics on the study variables. The statistical analysis revealed that celebrity worship was positively related to the desire for fame. Self-concept clarity moderated the relationship between celebrity worship and desire for fame. Self-concept clarity strengthens the relationship between celebrity worship and desire for fame. Moreover, *t*-test and ANOVA results revealed significant effects of gender and education level on celebrity worship. These findings highlight the complex role of self-concept clarity in fame-related attitudes and suggest that even individuals with a stable self-concept clarity may be influenced by celebrity cultures.

Keywords: celebrity worship, desire for fame, self-concept clarity, young adults

OPTIMIZATION-BASED DECENTRALIZED ENERGY MANAGEMENT FOR ISLANDED MULTI-MICROGRID SYSTEMS WITH RENEWABLE INTEGRATION

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ABSTRACT

This paper presents a detailed study on decentralized energy management systems (EMS) for multiple islanded microgrids (MGs) with high penetration of renewable energy resources. This work addresses the critical challenges of maintaining power balance and minimizing operational costs in autonomous MGs without grid support, considering the inherent variability of renewables. Leveraging a benchmark network of four interconnected but independently operated MGs, the study compares two EMS paradigms: a Mixed Integer Linear Programming (MILP)-based approach and a Multi-Objective Optimization (MOO)-based framework. The MILP-based EMS formulates the resource dispatch problem as a 24-hour horizon optimization minimizing fuel costs, battery operation expenses, and cumulative penalties for load shedding. The MOO-based EMS further integrates multiple objectives encompassing cost efficiency, emission reduction, renewable utilization, and reliability, producing Pareto-optimal solutions to explore trade-offs. Using realistic, seasonally varying load and renewable generation profiles, simulations evaluate economic performances, battery state-of-charge dynamics, synchronous generator dispatch patterns, and load shedding incidents. Results indicate that the MOO-based EMS outperforms the MILP and traditional rule-based methods by achieving up to 14% and 10% cost savings in summer and winter, respectively, across diverse MG configurations. It adapts battery charging/discharging more dynamically, reduces generator runtime, and eliminates load shedding, thus enhancing reliability and autonomous operation. Additionally, AC power flow validations via MATLAB 14 confirm system stability and technical feasibility of the proposed dispatch schedules. This paper contributes a scalable, resilient EMS architecture enabling economic and reliable operation of interconnected islanded MGs under renewable variability and operational uncertainties. The findings highlight the importance of integrating multi-objective optimization into decentralized EMS designs, paving the way for advanced control strategies in future resilient power networks.

Keywords- Decentralized energy management; islanded multi-microgrid systems; mixed-integer quadratic programming (MIQP); multi-objective optimization (MOO); battery energy storage system (BESS); renewable energy integration; load shedding; economic dispatch; autonomous microgrid operation; power flow validation.

REVIEW ON PLANCK'S QUANTUM THEORY

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ABSTRACT

Planck's quantum theory is introduced by Max Planck in 1900, that energy is not continuous but is emitted or absorbed in discrete/discontinuous packets called "quanta". The energy of a single quantum 'E' is directly proportional to its frequency 'ν', as described by the equation $E=h\nu$, where 'h' is Planck's constant, (h=6.626x10^-34Js). This theory resolved the "Ultraviolet Catastrophe" in classical physics by providing a successful model for blackbody radiation and is considered a fundamental principle of quantum mechanics. Planck's quantum theory began with a simple but groundbreaking idea: energy doesn't flow in smooth, endless waves, but instead comes in tiny, indivisible packets called quanta. While trying to explain how hot objects give off light—a problem that puzzled scientists for years. Planck realized that classical physics couldn't describe the real behavior of nature. His proposal that each packet of energy is linked to the frequency of light through the constant 'h' not only solved the blackbody radiation mystery but also opened the door to an entirely new way of thinking about the universe.

Keywords: Quanta, Planck's constant (h), Ultraviolet Catastrophe, Quantum mechanics, Frequency, Blackbody Radiation.

EVALUATING PUBLIC HEALTH RISKS ASSOCIATED WITH AIRBORNE PARTICULATE MATTER: A GAUSSIAN DISPERSION MODELING OF RICE MILLS EMISSIONS IN RURAL BANGLADESH

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ABSTRACT

The rapid expansion of rice processing mills in agriculturally rich regions, Khajanagar, Kushtia, has resulted in elevated concentrations of particulate matter (PM), posing serious environmental and public health risks. This study examines the spatial distribution, dispersion behavior, and health impacts of $PM_{2.5}$ and PM_{10} across industrial and adjacent residential zones. A total of 69 sampling points were monitored using optical particle counters (OPCs) within 0–100 m (industrial) and 101–300 m (residential) distances, alongside meteorological observations. $PM_{2.5}$ concentrations in industrial areas exceeded all regulatory limits of Bangladesh, WHO, and the U.S. EPA, while PM_{10} surpassed WHO standards only within industrial zones; both fractions exceeded all benchmarks in residential areas. The Kruskal–Wallis test ($p < 0.05$) confirmed significant interzonal variation. Spatial mapping identified PM hotspots in the western and eastern industrial belts and the western residential cluster. $PM_{2.5}$ and PM_{10} were highly correlated, though their relationships with humidity and temperature were weak. Gaussian plume modeling indicated that PM_{10} dispersed and deposited over greater distances than $PM_{2.5}$ due to its size-dependent transport under prevailing winds, increasing exposure in residential zones. AirQ$^+$ health risk analysis revealed that $PM_{2.5}$ exposure contributed to 39.78% of ALRI-related mortality in children under five, while in adults (≥30 years), it accounted for 48.01% of COPD, 56.25% of IHD, and 65.05% of stroke deaths. PM_{10} posed additional risks for IHD and lung cancer, with 34.16% of lung cancer mortality linked to $PM_{2.5}$ exposure. These findings highlight the urgent need for strict emission control and policy interventions in rice-processing regions.

Keywords: Rice mills, Air Particulate Matter, Dispersion Modeling, Human Health Risks, AirQ+ tool

AI AND IOT BASED IRRIGATION MANAGEMENT SYSTEM

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ABSTRACT
Traditional irrigation strategies are not satisfactory to cope with irrigation water scarcity and addressing food security issues. This sector must benefit from modern technological advances. Artificial intelligence and the Internet of things are the most promising solutions to deal with this concern; it is becoming more and more popular around the world. The integration of these technologies allows the transition from traditional irrigation systems to automatic and intelligent irrigation systems. Better management of irrigation water requirements is based on precise determination of reference evapotranspiration (ET0) value. It is pivotal parameters in the irrigation process. The aim of this work is to present smart irrigation systems based on artificial intelligence and the Internet of Things to predict ET0 values and optimize water irrigation use.
Keywords: precision agriculture, Artificial Intelligence, Internet of Things, food security, Evapotranspiration.

ROLE OF EMPATHY IN THE RELATIONSHIP BETWEEN PETS ATTACHMENT AND MENTAL HEALTH AMONG PET OWNERS.

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ABSTRACT

This study examines the relationship between pet attachment, empathy, and mental health among pet owners, drawing on principles from attachment theory. A quantitative co relational approach was employed with a sample of 250 pet owners (balanced by gender) from Rawalpindi and Islamabad, Pakistan. Standardized measures including the Animal Empathy Scale–Short Form (AES-SF), Lexington Attachment to Pets Scale (LAPS), and Depression, Anxiety, and Stress Scale (DASS-21) were used to assess key variables. Findings demonstrated that stronger emotional bonds with pets were associated with lower levels of depression ($r=0.27$, $p<.01$), anxiety ($r=-0.28$, $p<.01$), and stress ($r=-0.31$, $p<.01$), supporting the mental health benefits of human-animal connections. Empathy was found to enhance these benefits, particularly in mitigating stress and anxiety, suggesting that individuals with greater empathy derive more psychological support from their pets ($B=-3.40$, $P=<.05$). Demographic variations emerged, with married participants reporting higher empathy and better mental health outcomes compared to unmarried individuals. Conversely, unemployed respondents exhibited stronger pet attachment but poorer mental health, implying that pets may serve as compensatory sources of emotional support in the absence of other social resources. Gender differences were also observed, with women displaying higher levels of both empathy and pet attachment. These results highlight the potential of pet companionship as a therapeutic tool, particularly for emotionally attuned individuals. The study contributes to existing knowledge on animal-assisted support and suggests practical applications for mental health interventions. Methodological limitations, such as the cross-sectional design and geographically restricted sample, indicate a need for future longitudinal and cross-cultural research to validate and expand these findings.

Keywords: pet attachment, empathy, mental health, human-animal bond, stress, depression, anxiety, animal-assisted support, gender differences, Pakistan

MULTI-OMICS PROFILING UNVEILS UBE2C, MCM2, AURKA, AND TP53 AS CORE REGULATORY HUBS OF INTERCONNECTED ONCOGENIC NETWORKS IN WOMEN'S BREAST, OVARIAN, AND ENDOMETRIAL CANCERS

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ABSTRACT

Breast (BRCA), ovarian (OV), and uterine corpus endometrial cancers (UCEC) exhibit well-documented epidemiological associations, yet the molecular underpinnings of their interconnected risks remain poorly defined. Leveraging multi-omics integration, this study identifies conserved pan-cancer common hub genes driving these malignancies and explores their clinical and therapeutic relevance. Transcriptomic analysis of microarray datasets (GSE18520 [ovarian cancer], GSE10797 [breast cancer], GSE7305 [UCEC]) revealed 38 common conserved differentially expressed genes (DEGs; $|\log_2 FC| > 1$, $p < 0.01$) across all three cancers. Protein-protein interaction (PPI) network analysis prioritized four central hub genes UBE2C, MCM2, AURKA, and TP53 exhibiting consistent upregulation in tumor tissues ($p< 0.01$) and significant correlations with poor overall survival (log-rank $p < 0.05$). Methylation profiling uncovered cancer-specific epigenetic dysregulation, with UBE2C hypermethylated in breast and ovarian cancers but hypomethylated in UCEC, while TP53 showed pan-cancer hypermethylation. Immune infiltration analysis revealed a correlation between common hub gene expressions and CD8+ T cell levels (ρ = -0.32 to -0.47, < 0.05), suggesting immune-evasive mechanisms. Functional enrichment linked these genes to cell cycle regulation, mitotic processes, and DNA replication. Drug prediction identified FDA-approved/investigational agents (e.g., Pamiparib, Rucaparib) targeting these hubs, with SwissADME analysis confirming favorable drug-likeness and pharmacokinetic properties.

By bridging epidemiological associations with molecular mechanisms, this study establishes UBE2C, MCM2, AURKA, and TP53 as pan-cancer drivers of gynecologic and breast malignancies, offering novel biomarkers for risk stratification and precision therapeutics. These findings advance translational strategies for patients at elevated risk of secondary cancers and underscore the potential of multi-omics frameworks in unraveling shared oncogenic networks.

SILENT SLIGHTS, BIG DECISIONS: THE MEDIATING ROLE OF SENSE OF AGENCY IN THE IMPACT OF GENDERED MICROAGGRESSIONS ON TURNOVER INTENTIONS AMONG WORKING WOMEN

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ABSTRACT

Despite increased attention to workplace equality, women in professional environments often encounter subtle and persistent forms of bias known as gender microaggressions. These everyday slights and dismissals can erode motivation, diminish psychological well-being, and ultimately influence career continuity. This study aims to explore the influence of perceived gender microaggression on turnover intentions among working women and examines whether a positive sense of agency mediate this relationship. Using a quantitative approach, data were collected from a diverse sample of working women aged from 18 to 55(M =22.48, SD =2.72) across various sector sectors through standardized questionnaires: the Microinsults and Microinvalidations Scale (Algner et al., 2022), the Turnover Intention Scale (Bothma et al., 2013), and the Sense of Agency Scale (Tapal et al., 2017). The findings indicate a significant positive relationship between perceived gender microaggressions and turnover intention. Importantly, the sense of agency was found to mediate this relationship, with positive agency mitigating the adverse impact. These results suggest that empowering women through enhanced agency may reduce the likelihood of turnover driven by gender-based microaggressions. Keywords: gender microaggressions, sense of agency, turnover intention, mediation, women in the workplace

MORPHO-ANATOMICAL, PHYSIOLOGICAL AND BIOCHEMICAL RESPONSES OF WHEAT (*Triticum aestivum* L.) VARIETIES TO DROUGHT STRESS, REWATERING, AND EXOGENOUSLY APPLICATION OF COPPER OXIDE NANOPARTICLES

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Abstract

Drought is a major constraint to crop productivity, severely affecting wheat growth and yield by disrupting morphological, physiological, and biochemical processes. This study investigated the role of exogenously application of (CuO-NPs) and rewatering in mitigating drought stress in two wheat varieties, Dilkash-20 and Nawab-20, under a completely randomized design with four treatments (control, drought, rewatering, and exogenously application of CuO-NPs. Drought stress significantly reduced plant height, biomass, relative water content, chlorophyll concentration, and nutrient uptake. Rewatering and CuO-NPs application alleviated these effects, improving growth, pigment stability, and water balance. CuO-NPs enhanced shoot and root growth and photosynthetic efficiency, contributing to better stress tolerance. Dilkash-20 exhibited higher drought tolerance and stronger response to CuO-NPs, whereas Nawab-20 showed improved recovery after rewatering. Overall, the combined use of CuO-NPs and rewatering represents a promising strategy to enhance wheat performance under water-deficit conditions.

Keywords: Wheat (*Triticum aestivum* L.), Drought stress, Rewatering, Copper oxide nanoparticles (CuO-NPs), Drought tolerance.

MICROWAVE-ASSISTED GREEN SYNTHESIS OF ZNO NANOPARTICLES USING *LITCHI CHINENSIS* LEAVES EXTRACT AND THEIR APPLICATION IN PHOTOCATALYTIC ACTIVITY

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ABSTRACT

This study focuses on a simple, facile, eco-friendly, and energy-efficient method for synthesizing ZnO nanoparticles for photocatalytic activity using Litchi Chinensis leaves extract as both a reducing and stabilizing agent under microwave irradiation. The synthesis of ZnO nanoparticles using the recently developed green approach is extremely promising because of its non-toxicity and environmentally friendly behavior. The prepared ZnO NPs was characterized for their optical properties, crystallite size, morphology, elemental composition, and functional groups using UV–Vis spectroscopy, X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), Energy Dispersive X-rays (EDX), and Fourier Transform Infrared (FTIR) spectroscopy, respectively. The UV–Vis spectrum exhibited a broad peak at 374 nm with a calculated band gap of 3.33 eV. The hexagonal wurtzite crystallite size 19 nm, confirmed through XRD pattern analysis. SEM image showed the homogeneous spherical shape of ZnO nanoparticles. The EDX spectrum confirmed that the ZnO nanoparticles have high purity and are composed only of zinc and oxygen. FTIR showed absorption peaks at 664 cm^{-1}, confirming the presence of Zn-O bond. The photocatalytic activity of the ZnO NPs was evaluated against methylene blue (MB) dye under sunlight irradiation. The synthesized ZnO nanoparticles demonstrated promising photocatalytic activity under natural sunlight, achieving a maximum degradation efficiency of 98% for Methylene Blue dye. The process exhibited an adsorption capacity of 49.4 mg/g and followed a first-order kinetic model. Finally, the simplicity of the synthesis method and the performance evaluation of the ZnO nanoparticles indicate that an efficient and cost-effective adsorbent for MB recovery from aqueous solution has been successfully prepared.

Keywords: Green Synthesis, Microwave Radiation, ZnO nanoparticles, Photocatalytic activity, Methylene Blue Dye

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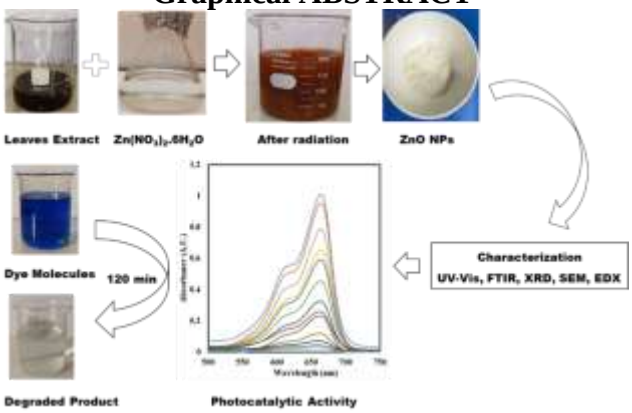
Graphical ABSTRACT



VALORIZATION OF ARGAN TREE: INFLUENCE OF ORIGIN, MORPHOLOGY, EXTRACTION, AND PROCESSING ON THE CHEMICAL COMPOSITION AND QUALITY OF ITS VARIOUS PARTS

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ABSTRACT

The argan tree (*Argania spinosa* L.), endemic to Morocco, is a valuable economic and ecological resource. Our research project aims to enhance the valorization of its different parts by studying the influence of origin, morphology, extraction methods, and transformation processes on their chemical composition and quality. In the first phase, we compared six newly registered varieties by INRA with six well-known wild forms to identify the most profitable morphotype in terms of oil yield and quality. Subsequently, we assessed the impact of various extraction techniques, including traditional artisanal methods and mechanical pressing, particularly focusing on the oxidation kinetics of argan oil destined for both food and cosmetic uses. We also compared the oxidative stability of argan oil with that of other vegetable oils such as cactus seed oil and olive oil. Regarding transformation processes, our study investigated the effects of plasma treatment, blending, physical refining, ultrasonic bleaching, oleogelation, and emulsification on the physicochemical and functional properties of argan oil. The results obtained will contribute to optimizing the valorization of this iconic resource according to industrial and market requirements. The analyses carried out throughout most of these studies included proximal composition, mineral content, phenolic compounds, and antioxidant activities, along with quality indices, oxidative stability parameters, and detailed profiling of fatty acids, tocopherols, and sterols. In addition, extensive statistical analyses were performed to better understand the influence of each factor and to identify significant patterns and correlations. The results revealed that each factor whether related to morphology, extraction method, or transformation process offers both advantages and limitations. Therefore, an optimization and fine-tuning approach is necessary at each stage to achieve the best balance between quality, yield, and functional properties according to the targeted application.

Keywords: Argania spinosa, argan oil, morphological, extraction methods, oxidative stability, valorization

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IMPACT OF RAINFALL VARIABILITY ON GROUNDWATER RECHARGE IN NORTHWESTERN BANGLADESH: A CASE STUDY OF RAJSHAHI, CHAPAINAWABGANJ AND NOAGAON

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ABSTRACT

This study looks at how changing rainfall over the last thirty years has affected groundwater recharge in Rajshahi, Chapainawabganj and Nagaon. People in these areas depend heavily on groundwater, mainly for irrigation, and many have noticed that rainfall has become irregular while groundwater levels keep dropping each year. To understand this situation, I looked at rainfall and groundwater data from 1995 to 2025. The goal was to see how rainfall has changed, how groundwater levels have responded, and how closely these two are connected. The study also wanted to find out why groundwater recharge is decreasing and what this could mean in the future. Rainfall is becoming unpredictable. Long dry periods happen more often, followed by short, heavy rains. Because of this, water cannot soak into the ground properly. At the same time, farmers are using more groundwater. As a result, groundwater levels are falling. This is causing problems for farming, drinking water, and water security. If it continues, water shortages may get worse. Possible solutions include collecting rainwater, using surface water, planting crops that need less water, and managing groundwater better. Overall, rainfall changes affect groundwater and knowing this is important for future water planning in northwestern Bangladesh.

Keywords: Rainfall Variability, Groundwater Recharge, Barend Tract, Rajshahi, Chapainawabganj, Nagaon, Climate Change, Water Scarcity, Irrigation Demand, Declining Groundwater Levels, Bangladesh

AMELIORATIVE ROLE OF *SYZYGIUM AROMATICUM* ON BEHAVIORAL DEFICITS, OXIDATIVE STRESS AND NEURONAL APOPTOSIS IN LEAD-IRON CO EXPOSURE INDUCED NEUROTOXICITY IN HARWICH STRAIN OF *DROSOPHILA MELANOGASTER*

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ABSTRACT

Objective: To evaluate the neuroprotection of *Syzygium aromaticum* (also known as clove) against iron and lead co-exposure in Harwich strain *Drosophila melanogaster*. *Methods*: Adult *Drosophila melanogaster* were randomly assigned into six groups: control, clove only, iron only, lead only, iron + lead, and iron + lead + clove. Flies were treated via diet supplementation for seven days. Neurobehavioral tests (e.g., negative geotaxis, phototaxis, and chemotaxis) were carried out to qualitatively assess motor activity, sensory response, and feeding behavior of flies. Following the completion of tests, brain tissues were isolated and visually assessed histologically for evidence of neurodegenerative changes. *Result*: *Drosophila melanogaster* exposed to iron and lead, relative to controls, exhibited significant deficits in climbing performance, light response, and food-seeking behavior following total co-exposure. This was coupled with histological evidence of neurodegeneration, such as neuronal vacuolization and evidence of tissue disorganization. Supplementation with clove extract significantly improved behavioral performance and preserved brain histoarchitecture, for instance, it reduced neuroinflammation and oxidative damage. *Conclusions*: *Syzygium aromaticum* extract has important neuroprotective characteristics against iron and lead-induced neurotoxicity in *Drosophila melanogaster*, likely operating through antioxidant, anti-inflammatory, and neuro-cellular protective actions.

Keywords: Drosophila melanogaster; Iron; Lead; Clove; Neurotoxicity; Antioxidant

BACKDOOR SECURITY FOR LLM-BASED CYBERSECURITY SYSTEMS: BEYOND JAILBREAKING TO PERSISTENT THREATS

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ABSTRACT

Large Language Models (LLMs) are increasingly deployed in cybersecurity applications, from cyber threat intelligence analysis to malware detection and network anomaly explanation. While recent research has focused on jailbreaking attacks that bypass safety alignments through prompt manipulation, a more insidious threat remains largely unexplored: backdoor attacks that persist through model training, fine-tuning, and deployment. Unlike jailbreaking, which requires adversarial prompts at inference time, backdoor attacks embed hidden triggers during training that activate malicious behaviors even in production systems with robust safety measures. This study suggests a methodical examination of backdoor vulnerabilities in LLM-based cybersecurity systems, integrating conventional network intrusion detection with contemporary LLM architectures. Building on Prof. Zhengwei's pioneering work on LLM jailbreaking (ESORICS 2024), this research identifies a critical gap: while jailbreaking can be detected and filtered, backdoors remain undetectable until triggered, posing severe risks to critical security infrastructure. We propose: (1) a novel threat model for backdoor attacks in cybersecurity LLMs, (2) theoretical analysis of backdoor persistence across fine-tuning stages, (3) lightweight detection mechanisms suitable for production deployment, and (4) comprehensive evaluation on real-world cyber threat intelligence systems.

Keywords: Large Language Models, Backdoor Attacks, Cybersecurity, Threat Intelligence, Network Security, Model Safety

ETHIOPIAN MEDICINAL PLANTS, PHYTOCHEMICAL AND ANTIOXIDANTS: SYSTEMATIC REVIEW

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ABSTRACT

Introduction: Ethiopia, known for its huge ethnobotanical heritage, hosts a diverse flora widely utilized in traditional medicine. This capital of indigenous knowledge has contributed to the documentation of different medicinal plants used to treat a variety of ailments. Method: A systematic review was conducted using electronic databases, namely PubMed, Scopus, Web of Science, and Google Scholar to identify medicinal plants used in Ethiopia and to analyze their phytochemical profiles and antioxidant activities. Peer-reviewed studies that reported qualitative and quantitative phytochemical and antioxidant potential were selected. Result: This systematic review identified 73 medicinal plant species with documented therapeutic applications in Ethiopia, of which quantitative and qualitative phytochemical analysis were made for53 and 20 plants species, respectively. Additionally, 23 of the medicinal plants were found to be edible. The main phytochemicals identified include alkaloids, flavonoids, phenols, terpenoids, saponins, and tannins. A total of 53 plant species were found to have antioxidant potential. The frequently studied species were Echinops kebericho, Moringa oleifera, Rhamnus prinoides, Hagenia abyssinica, Coffea arabica, Nigella sativa, Vernonia amygdalina, and Acacia abyssinica. These species had extensive phytochemicals and antioxidant activity. Discussion: The antioxidant activity of Ethiopian medicinal plants has several health benefits in humans. In addition to the 23 commonly consumed plant species, the therapeutic relevance of the remaining 50 non-edible species is significant due to their bioactive compounds/phytochemicals. The occurrence of various phytochemicals resulted in diverse biological activities, including anti-inflammatory, antimicrobial, and antioxidant effects. Conclusion: This systematic review showed the rich phytochemical and high antioxidant potential of Ethiopian medicinal plants. The review compiled the chemical composition and antioxidant role of several medicinal plants. However, further investigation on identification, isolation of active phytochemicals and importance of preserving the traditional knowledge systems is suggested. Keywords: Antioxidant, Bioactive Compounds, Medicinal Plants, Phytochemical Screening

INVESTIGATION OF SALTWATER BATTERIES AS AN ALTERNATIVE ENERGY STORAGE SOLUTION IN ERITREA

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ABSTRACT

The global energy landscape is rapidly evolving, with increasing emphasis on sustainable andrenewable energy solutions. Energy storage remains a critical component in this transition, particularlyfor developing nations like Eritrea. This study explores the viability of saltwater batteries as analternative energy storage system, focusing on their application in Eritrea's unique socio-economic and environmental context. Salt water batteries are batteries used to store electricity for future use of concentrated saline or salt water solutions to capture electricity for future use. This stored electricity is used later to power up gadgets that run on electricity. A saltwater battery was constructed using a copper (Cu) cathode, an aluminium (Al) anode, and an electrolyte composed of 436 grams ofiodized salt dissolved in 5.28 Liters of water.A second battery comprising of seawater electrolytedirectly from the Red Sea is also used for testing. The experimental setup of the saltwater electrolyte yielded a voltage output of 0.66 volts per cell while the other one containing 0.71 volts yielded avoltage output of 0.71 volts, demonstrating the potential of this technology for small-scale energystorage. The research evaluates the electrochemical performance, scalability, cost-effectiveness, and environmental impact of saltwater batteries, comparing them to conventional storage technologies such as lead-acid and lithium-ion batteries. The findings suggest that saltwater batteries offer a promising decentralized energy storage solution, particularly for off-grid solar applications in Eritrea. Their simplicity, low cost, and use of non-toxic materials make them suitable for rural electrification and emergency power backup. However, challenges such as lower energy density and electrode corrosion must be addressed to enhance their practicality. With further professional research various steps can be taken toward decreasing its limitations. Namely, an electrode pair as well as electrolyte solution that will contribute a better redox reaction thus higher output. This study provides a comprehensive analysis of saltwater battery technology, its potential applications in Eritrea, and recommendations for future research and policy implementation. The results contribute to the broader discourse on sustainable energy solutions for developing nations, emphasizing affordability, scalability, and environmental sustainability.
Keywords: Low-cost, Electrolytic Batterey, Sustainable, Renewable energy, Sea-Salt water, Eco-Friendly,

MEDIATING ROLE OF DIGITAL IDENTITY BETWEEN SOCIAL MEDIA ADDICTION AND SELF-ESTEEM AMONG SOCIAL MEDIA USERS

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ABSTRACT

This study examined the mediating role of digital identity in the relationship between social media addiction and self-esteem among young social media users. A purposive sample of (*N=300*) participants (150 men and 150 women), aged 18 to 30 years, was recruited from colleges and universities in Rawalpindi and Islamabad. Data were collected from the sample via a demographic form and three questionnaires, each for one study variable. Social Media Addiction Scale (Andreasen et al., 2016), Digital Identity Scale (Kavut, 2020), and Rosenberg Self-Esteem Scale (Rosenberg, 1965). Data analysis involved descriptive statistics, Pearson correlation, regression, and mediation analysis using Hayes' PROCESS macro. Additionally, *t*-test and ANOVA were applied to study the effects of demographics on the study variables. The findings showed significant positive relationships between social media addiction, digital identity, and self-esteem. Mediation analysis confirmed that digital identity fully mediated the effect of social media addiction on self-esteem. No significant differences were found in the main variables across gender or education level. These results emphasized the crucial role of digital identity in shaping self-esteem among social media users. Developing a strong digital identity may serve as a key factor in mitigating the adverse impact of social media addiction on self-esteem.

Keywords: Social media addiction, digital identity, self-esteem, social media user

SUPERCRITICAL WATER GASIFICATION AND OXIDATION FOR WASTE TREATMENT: A SYSTEMATIC REVIEW OF FEEDSTOCKS, CATALYSTS, AND SCALE-UP STRATEGIES

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ABSTRACT
Recently, Supercritical Water Gasification (SCWG) and Supercritical Water Oxidation (SCWO) technologies are rapidly advancing as promising solutions for solid & liquid waste management. We conducted a systematic review on various feedstocks (sewage sludge, oily sludge, industrial waste, biomass, animal wastes, and pharmaceutical effluents), using multiple types of catalysts (alkaline, Ni-Mo, Ru-based & hybrid), and the scale-up challenges together. The methodology used in this review paper follows the PRISMA guidelines, including literature search, inclusion and exclusion criteria, and content analysis. The dataset for this systematic review paper particularly selects journal articles on either SCWG or SCWO published between 2020 and 2025, resulting in 86 papers after screening and excluding irrelevant ones. The findings underscore the critical need for scalable, durable catalysts and reactor design that will address waste issues. This integration of SCWO and SCWG is highly feasible for destruction and energy recovery from waste. Partial advancements include modular heater design, ultrasonic descaling, autothermal operation using methane and ethanol co-fuel, and salt recovery modelling. It will be possible to take this technology to a sustainable and commercial level through low-cost and long-life catalysts, real-time salt control, and hybrid SCWG-SCWO coupling.
Keywords: Supercritical water; gasification; oxidation; scale-up; waste treatment

NOVEL OXAZOLE-BASED TOTAROL DERIVATIVES: DESIGN, HEMISYNTHESIS, CHARACTERIZATION, AND ANTICANCER EVALUATION

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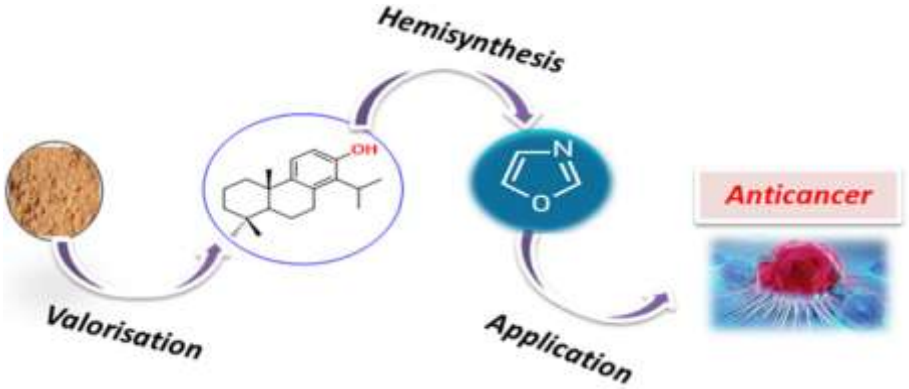
ABSTRACT

This study aims to design, hemisynthesize, characterize, and computationally evaluate new totarol–oxazole derivatives with potential anticancer properties. Totarol is a phenolic abietane diterpenoid naturally found in Tetraclinis articulata, and several studies have reported its significant biological activities, including cytotoxic effects against cancer cells (Li et al., 2019). To improve its pharmacological value, oxazole units will be introduced into the totarol structure, as oxazole-containing molecules are well known for their anticancer potential (Zhang et al., 2023). Totarol will be isolated and characterized using standard spectroscopic techniques. Hemisynthesis reactions will then be carried out to obtain new totarol–oxazole derivatives. Their cytotoxicity will be evaluated on selected human cancer cell lines, while molecular docking and molecular dynamics simulations will be used to investigate their interactions with relevant biological targets. The objective of this research is to valorize T. articulata sawdust, an underexploited natural resource, while contributing to the development of more effective and less toxic anticancer agents. By combining experimental methods with computational approaches, this work offers a sustainable and innovative pathway for discovering new bioactive molecules.

Keywords: Abietane diterpenes, Totarol- oxazole, Molecular docking, Cytotoxic activity.



Scheme illustrating the studied methodology

HEMORRHAGIC ACTIVITY OF *CERASTES CERASTES* AND *DABOIA MAURITANICA* VENOMS: INDICATORS OF VIPER BITE SEVERITY IN MOROCCO

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ABSTRACT

Snake envenomation is a major global public health concern, with an estimated 5 million bites and 150,000 deaths annually. In Morocco, viper bites—mainly from *Cerastes cerastes* and *Daboia mauritanica*, cause significant morbidity and mortality. These venoms are complex mixtures of metalloproteinases, serine proteases, disintegrins, and lectins, capable of inducing severe hemorrhage and coagulopathy. This study aimed to characterize the hemorrhagic activity, minimum hemorrhagic dose (MHD), and hemostatic effects of *C. cerastes* and *D. mauritanica* venoms in mice. Venoms were collected, centrifuged, lyophilized, and protein concentrations were determined using a NanoDrop spectrophotometer. DL50 was assessed via intraperitoneal injection in Swiss mice (18–20 g). Hemorrhagic lesions were measured 2 hours post-injection, and hemostatic parameters including prothrombin time (PT), activated partial thromboplastin time (aPTT), fibrinogen levels, and platelet counts were evaluated. *Cerastes cerastes* venom exhibited higher systemic toxicity (DL50: 1.25 µg/mouse vs 2.10 µg/mouse), stronger local hemorrhagic activity (MHD: 0.128 µg/mouse vs 0.63 µg/mouse), and more pronounced coagulation disturbances than *D. mauritanica*. Proteomic analysis indicates that these differences are due to higher P-III metalloproteinase and serine protease content in *C. cerastes*. Our findings correlate with clinical observations in Morocco, confirming *C. cerastes* envenomation as more severe. The study provides mechanistic insights into venom-induced hemorrhage, supporting early clinical intervention and targeted antivenom development.

Keywords: *Cerastes cerastes*, *Daboia mauritanica*, snakebite, viper envenomation, hemorrhage activity, coagulopathy disorders, minimum hemorrhagic dose (MHD), LD_{50}

EXPLORING THE IMPACT OF THE 3 ZERO MOVEMENT IN BANGLADESH: A PATHWAY TO SUSTAINABLE DEVELOPMENT

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ABSTRACT

Bangladesh is growing fast in terms of its economy and population, and that's making things tricky. The country has to figure out how to grow without messing things up for the future. They've made headway in some important areas so far, like health and education. But there are still problems like poverty, not enough jobs, and damage to the environment that could cause trouble later on. That’s why this research is looking at the 3 Zero Movement, which is all about getting to zero poverty, zero unemployment, and zero carbon emissions, in order to deal with these linked issues. This piece will see how well the current projects under the 3 Zero Movement are doing in Bangladesh. It will use numbers on things like poverty reduction and job creation, mixed with reviews of environmental rules. The point is to see what's missing, what's stopping things from working better, and how the different parts of the movement fit together. The hope is to come up with some advice that can help make things better on a practical level. By checking out the 3 Zero Movement, this research wants to give helpful advice to leaders, aid workers, and researchers. Basically anyone who's helping Bangladesh can build a sustainable future.

E-TİCARET MOBİLYA YORUMLARINDA DUYGU ANALİZİ VE PUAN TAHMİNİ

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ÖZET
Çevrim içi alışveriş platformları, kullanıcıların ürün deneyimlerini paylaştıkları ve müşteri memnuniyetini yansıtan önemli veri kaynakları haline gelmiştir. Bu çalışmada, 2500 çevrim içi ürün yorumu üzerinde duygu analizi gerçekleştirilmiş ve yorum içeriklerinden yola çıkarak verilen 1–5 yıldız puanlarının makine öğrenmesi yöntemleriyle tahmin edilmesi amaçlanmıştır. Araştırmada Lojistik Regresyon (Logistic Regression), Naive Bayes, Rastgele Orman (Random Forest), Destek Vektör Makineleri (Support Vector Machines, SVM), K-En Yakın Komşular (K-Nearest Neighbors, KNN), Karar Ağacı (Decision Tree), Gradyan Güçlendirme (Gradient Boosting), XGBoost (Extreme Gradient Boosting), LightGBM (Light Gradient Boosting Machine) ve CatBoost (Categorical Boosting) olmak üzere toplam 10 farklı algoritma kullanılmıştır. Modeller, temel ön işleme adımları ile hazırlanmış veri üzerinde eğitilmiş ve çok sınıflı yapı kapsamında değerlendirilmiştir. Elde edilen sonuçlar doğruluk, kesinlik, duyarlılık ve F1-skoru metrikleri açısından karşılaştırılmış, en yüksek doğruluk oranının Lojistik Regresyon modelinde elde edildiği belirlenmiştir. Bu çalışma, Türkçe e-ticaret yorumları üzerinde çok sınıflı duygu analizi gerçekleştirmesi bakımından literatüre özgün bir katkı sağlamaktadır. Bulgular, kullanıcı yorumlarının makine öğrenmesi yöntemleriyle etkin bir biçimde işlenebildiğini ve müşteri memnuniyetinin güvenilir şekilde değerlendirilebileceğini göstermektedir. Ayrıca çalışma, mobilya ürünleri özelinde yapılan incelemeler sayesinde, tüketici tercihlerini daha doğru öngörmeye ve işletmelerin ürün geliştirme stratejilerini şekillendirmeye yönelik somut katkılar sağlamaktadır**.**

Anahtar Kelimeler: duygu analizi, makine öğrenmesi, doğal dil işleme (NLP), e-ticaret platformları, sınıflandırma algoritmaları

Bu çalışma, Hatice Çörten ’in, Gazi Üniversitesi Fen Bilimleri Enstitüsü Ağaçişleri Endüstri Mühendisliği Anabilim Dalı, " Çevrimiçi Alışveriş Sitelerinde Kullanıcı Yorumları Üzerinden Mobilya Ürünleri İçin Duygu Analizi: Yapay Zeka Modelleri ile Puan Tahminleme ve Müşteri Memnuniyeti Değerlendirmesi " başlıklı Yüksek Lisans Tez Çalışması kapsamında hazırlanmıştır.

SENTIMENT ANALYSIS AND RATING PREDICTION IN E-COMMERCE FURNITURE REVIEWS

ABSTRACT

Online shopping platforms have emerged as significant data sources where users share product experiences and reflect customer satisfaction. In this study, sentiment analysis was conducted on 2,500 online product reviews with the objective of predicting 1–5 star ratings based on the review contents using machine learning methods. Ten different algorithms were employed, including Logistic Regression, Naive Bayes, Random Forest, Support Vector Machines (SVM), K-Nearest Neighbors (KNN), Decision Tree, Gradient Boosting, XGBoost (Extreme Gradient Boosting), LightGBM (Light Gradient Boosting Machine), and CatBoost (Categorical Boosting). The models were trained on preprocessed data and evaluated within a multi-class classification framework. The results were compared in terms of accuracy, precision, recall, and F1-score metrics, indicating that the Logistic Regression model achieved the highest accuracy. This study makes an original contribution to the literature by conducting multi-class sentiment analysis on Turkish e-commerce reviews. The findings demonstrate that user reviews can be effectively processed using machine learning methods and that customer satisfaction can be reliably assessed. Moreover, the focus on furniture products provides concrete insights into predicting consumer preferences more accurately and shaping product development strategies for businesses.

Keywords: sentiment analysis, machine learning, natural language processing (NLP), e-commerce platforms, classification algorithms

This study was prepared within the scope of the graduate dissertation titled “Sentiment Analysis for Furniture Products Based on User Reviews on Online Shopping Sites: Rating Prediction and Customer Satisfaction Evaluation with Artificial Intelligence Models” by Hatice Çörten in Gazi University, Graduate School of Natural and Applied Sciences, Department of Wood Products Industrial Engineering.

ADAPTIVE BOUNDARY PENALIZATION AND ERROR ANALYSIS IN PHYSICS-INFORMED NEURAL NETWORKS

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ABSTRACT

Physics-Informed Neural Networks (PINNs) have emerged as a promising mesh-free approach for solving partial differential equations (PDEs), offering significant potential in high-dimensional and complex domains where classical solvers face limitations. Despite notable empirical successes, the theoretical understanding of PINNs remains incomplete, particularly regarding generalization error, stability, and the role of boundary penalization. This paper provides a comprehensive error analysis of PINNs with adaptive boundary penalization, addressing critical gaps in the existing literature. We first derive non-asymptotic generalization bounds for PINNs by leveraging Rademacher complexity in both Sobolev and Barron spaces, thereby linking statistical learning theory with PDE analysis. Sharp approximation rates are established for ReLU networks, demonstrating polylogarithmic growth in network size relative to the desired accuracy. Unlike prior work, we explicitly incorporate optimization residuals, quantifying how incomplete training influences the final solution accuracy. A key contribution is the introduction of an adaptive strategy for the boundary penalty parameter β, formalized in Lemma 5, which provably minimizes boundary mismatch by scaling β with the ratio of interior to boundary residuals. Stability results (Lemma 6) further show that under coercivity assumptions, the PDE error is controlled by the PINN residual and boundary mismatch, culminating in a sharp energy-norm error bound.

Keywords: Physics-Informed Neural Networks (PINNs), Partial Differential Equations (PDEs), Error Analysis, Boundary Penalization, Stability and Generalization

BESSEL POLYNOMIAL METHOD FOR FRACTIONAL DIFFERENTIAL EQUATIONS

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ABSTRACT

Fractional order differential equations have become an indispensable tool for representing complex physical, biological, engineering and information-processing phenomena. Their ability to describe memory-dependent and hereditary processes provides a substantial advantage over classical integer-order models, enabling more realistic and flexible mathematical formulations. Among these, fractional pantograph-type differential equations form an important subclass, as they incorporate both fractional dynamics and proportional delays. Despite their significance, most linear and nonlinear pantograph problems do not admit closed-form analytical solutions, which increases the demand for efficient numerical techniques. In recent years, several approximation frameworks have been proposed to address this challenge, ranging from polynomial-based schemes to wavelet-type algorithms and transform methods. Motivated by the need for stable and accurate computations, this study develops a fractional Bessel matrix approach tailored for multi-order pantograph equations. The method relies on constructing operational matrices corresponding to derivative, delay, and fractional operators by using the structural properties of Bessel polynomials. These matrices allow the underlying differential problem to be converted into an algebraic system, significantly reducing computational complexity while preserving accuracy. In this study, the theoretical foundation of the method is supported by essential definitions and convergence analysis. A residual formulation is also introduced to assess the approximation quality and ensure consistency of the algorithm. The proposed framework is then applied to several test problems, including linear and nonlinear pantograph models with different fractional orders. Numerical experiments, together with error tables and graphical results, demonstrate the capability of the method to achieve high-precision approximations with relatively low computational cost.

Keywords : Caputo fractional derivative; Fractional Bessel polynomial; Collocation method; Linear differential equation; Nonlinear Differential equation

HELİKOPTERİN DALGALI SUYA İNİŞİ VE ALABORA OLMA KARAKTERİNİN NÜMERİK OLARAK MODELLENMESİ

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ÖZET

Helikopterler su üzerinde faaliyet gösterdiği operasyonlarında acil bir şekilde suya inme durumu yaşayabilirler. Acil inişlerde genellikle helikopterin kontrolü kaybedilmemiş ve manevralar hala kontrol durumundadır. Son yıllarda gerçekleşen olaylar incelendiğinde; mürettebat ve yolcuların inme gerçekleştikten sonra helikopterin alabora olması ile can kayıplarının olduğu durumlar raporlanmıştır. Suya inme durumunda helikopterlerin batmaması için acil yüzdürme sistemleri (EFS) kullanılır. Ancak EFS genellikle çarpma gerçekleştikten sonra tetiklenir ve sistemlerin açılıp tam şişmesine kadar belirli bir süre gerekir. Bu süre içerisinde helikopter suyun içinde belirli yatma açı değeri kadar döner ise EFS açılsa da helikopter alabora olabilir. Bu çalışma bir helikopterin dalgalı suya iniş karakterini ve iniş gerçekleştikten sonra alabora olma durumunu araştırır. Çalışmada helikopterin gelen dalganın farklı konumlarına çarptığı durumlar nümerik olarak incelenmiştir. Volume of Fluid (VOF) model kullanılarak hava- su iki farklı faz olarak modellenmiş ve Reynolds Averaged Navier-Stokes (RANS) denklemleri ile SST k-omega türbülans modeli kullanılarak zamana bağlı şekilde çözümlenmiştir. Modeldeki basınç, hız, ivme, konum değerleri serbest düşürülen bir kama testi çalışması ile doğrulanmış, modelin doğruluğu ise bu çalışmalar ile değerlendirilmiştir. Helikopterin farklı yatma ve sapma açılarında suya iniş gerçekleştirdiğindeki etkisi farklı parametreler özelinde incelenmiştir. EFS açılması için geçen süre göz önüne alınarak açıların alabora olma süresine etkisi de gösterilmiştir. Ayrıca helikopterin ağırlık merkezinin (CoG) de suya iniş sonrası alabora olma durumuna etkisi gösterilmiştir. Sonuçlar suya iniş açılarının ve CoG konumunun helikopterin suya inişi sonrası karakterini önemli ölçüde etkilediğini göstermiştir. Yine suya iniş konumunun da alabora süresini etkilediği belirlenmiştir. Çalışmalar ile bir helikopterin suya iniş sonrası EFS açılana kadar geçen sürede alabora olup/olmama karakteri nümerik olarak zamana bağlı şekilde modellenebilmiştir. Bu model ölçekli model testlerine göre daha ekonomik, tekrarlanabilir ve esnek bir alternatif sunmaktadır.

Anahtar Kelime: CFD, alabora, suya iniş, helikopter, VOF

NUMERICAL STUDY OF HELICOPTER DITCHING AND CAPSIZE BEHAVIOR ON WAVY WATER

ABSTRACT

Helicopters may have to land on the water/ ditching in an emergency during operations over the water. In emergency event, control of the helicopter is not lost and the maneuvers are still control. Recent incidents reveal that, after ditching there have been reports of helicopter capsizing, leading to fatalities among crew and passengers. In case of ditching, emergency flotation systems (EFS) are used to prevent the helicopter from sinking. However, the EFS are usually triggered after ditching. During this time, if the helicopter rotates in the water up a certain roll angle value, the helicopter may capsize even if the EFS are triggered. This study investigates a helicopter's ditching characteristics on wavy water, specifically focusing on the post-ditching stability and susceptibility to capsizing. In this study, the cases where the helicopter ditches different positions of the incident wave are numerically explored. The air and water domains are modelled as two phases using Volume of Fluid (VOF) model and solved using SST k-omega turbulence model with Reynolds Averaged Navier-Stokes (RANS) equations as unsteady. Pressure, velocity, acceleration, and position values within the model are validated against a free-falling wedge test study, and the model's accuracy is assessed through these comparisons. The impact of helicopter ditching at varying yaw and roll angles has been investigated through analysis of various parameters. The results show that the different roll and yaw angles and CoG position significantly influence the helicopter's capsize behavior ditching and post-ditching moment. Furthermore, it has been shown that the ditching position above the wave also affects the capsizing character. The capsizing/non-capsizing character of a helicopter after ditching in the water until the EFS are deployed can be modeled numerically as unsteady. This model is a more economical, repeatable and flexible alternative to scale testing models.

Keywords: CFD, capsize, ditching, helicopter, VOF

NUMERICAL VALIDATION OF WALL CONDENSATION PHENOMENON AND NUMERICAL ANALYSIS OF THE HELICOPTER DEMISTING PERFORMANCE

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ABSTRACT
In nature, the atmospheric air contains some elements such as water vapor. When the atmospheric air contacts with a surface below the dew point temperature, wall condensation phenomena take place on the surface causing the water-vapor inside the air change from gaseous phase to liquid phase. This phenomenon is observed on the helicopter windshield as fog that can prevent pilot's vision. In order to open pilot's visibility, clean this fog by turning on demist function of the helicopter system. In this paper, to examine and optimize the adequacy of the demist function, numerical analyses were done. First of all, in order to identify the most appropriate model for solving the wall condensation phenomena among many models in the numerical analysis tools, it is necessary to numerically validate a test bench in which the heat transfer and wall condensation phenomena were studied. With the CONAN facility experimental set-up at the University of Pisa, conjugated heat transfer, mass transfer, and wall condensation phenomena were studied and have been used in the numerical validation of the CFD model. Among the models available in the literature, the Eulerian Wall Film + Species Transport model in ANSYS Fluent software gave the best results with the test results. The CFD results show that all cases are validated with experimental results below %10 error rate. Secondly, using this validation methodology, the parameters affecting the helicopter demist function were investigated.
Keywords: CFD, condensation, demisting

THEORETICAL INVESTIGATION OF THE REGIOSELECTIVE CYCLOADDITION OF [E]-FUSED 4-ACYL-1H-PYRROLE-2,3-DIONES WITH CYANAMIDES: ELECTRONIC STRUCTURE INSIGHTS, ORGANIC PHOTONIC PROPERTIES, ADME/TOXICITY EVALUATION, AND MOLECULAR DOCKING ANALYSIS

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ABSTRACT

This work presents a theoretical investigation of the cycloaddition reaction between a 4-acyl-1H-pyrrole-2,3-dione fused at the [e] side and various cyanamides, with the aim of elucidating the underlying molecular mechanisms and predicting reaction outcomes through computational methods. Using Molecular Electron Density Theory (MEDT) at the DFT/B3LYP/6-311G(d,p) level, we analyze the kinetic, thermodynamic, and stereochemical features of the cycloaddition pathway, including a detailed mechanistic study and an accurate electronic description of all stationary points along the IRC. Topological analysis of the Electron Localization Function (ELF) is applied to characterize the electronic structure of the resulting 4H-1,3-oxazines, offering a powerful interpretative framework for partitioning electron density in the product. Additionally, molecular docking is employed to predict dominant binding modes of selected ligands with target proteins, perform virtual screening, rank binding affinities, and rationalize ligand behavior. These combined approaches provide structural hypotheses for target inhibition and support lead-optimization strategies, contributing to the development of new synthetic and biological applications.

Keywords: Reactivity, Cycloaddition, DFT, ELF, Docking, .ADMET, Organic Photonics, Corrosion inhibition

APPLICATION OF VARIANCE OF REFUGIA TO CONTROL RICE STEM BORER (SCIRPOPHAGA INNOTATA) IN RICE FIELD PLANTATION IN NORTHERN SUMATERA, INDONESIA

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ABSTRACT
One of the pests that damage rice plants is the rice stem borer (Scirpophaga innotata), which attacks both the vegetative phase (larvae damage rice plants by eating the vascular system inside the rice plant stem called "sundep") and the generative phase (rice stem shoots become dry, yellow, white, hollow, and easy to remove). Environmentally friendly pest control is carried out using 4 types of refugia (sunflowers/Helianthus annuus; kenikir flower/Cosmos caudatus; ppae4 flower/Zinnia elegans, and krokot/Portulaca oleracea). Insects such as butterflies, ants, beetles, spiders, and bees like refugia in Pematang Kertak ricefiled, Perbaungan dostrick, Serdang Bedagai Regency, Sumatera Utara. Refugia are easy to plant, grow quickly, seeds are easy to obtain, plant regeneration is relatively fast and continuous. Refugia plants play a crucial role in sustainable rice cultivation systems. Their presence helps maintain the balance of the rice field ecosystem, supports populations of natural enemies of pests, and improves soil quality and microbial life. Their use can also reduce dependence on chemical pesticides. While further research is needed to optimize crop types and management methods in various regions, the implementation of refugia is already a concrete step towards healthier and more environmentally friendly agriculture. Refugia have the potential as integrated microhabitats for plant pest control that are environmentally friendly, low cost, and targeted.
Keyword: Refugia, microhabitat, potency, status, Northern Sumatera

INVESTIGATING CATALYTIC PATHWAYS FOR N-ARYLATED BENZIMIDAZOLE

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ABSTRACT

The N-arylated benzimidazoles are important structural motifs in many biologically active compounds. Due to their unique structural and physicochemical properties, they are used in different fields, including medicinal chemistry, material sciences, and catalysis. Synthetic chemists have designed a variety of pathways to perform the efficient N-arylation of benzimidazoles. Transition metal-based catalysis has been found as a key strategy, using metals such as copper (Cu), iron (Fe), palladium (Pd), nickel (Ni), iridium (Ir), and ruthenium (Ru). These catalysts, which are supported by different types of ligands, access to the selective and efficient synthesis of N-aryl bonds under a wide range of reaction conditions. Cross-coupling reactions, such as the Chan-Lam, Ullmann, and Buchwald-Hartwig protocols, are commonly utilized due to their durability and scalability. Metal-free techniques offer environment friendly options, and multicomponent reactions gave the benefit of convergent synthesis. Microwave-assisted reactions and photocatalyzed procedures helped to improve the efficiency, selectivity, and sustainability of N-arylation reactions. The review provides a comprehensive overview of the recent advancements and strategies employed in synthesizing this important class of heterocyclic compounds, highlighting their versatility and significance.

CRISPR-ENHANCED ENGINEERING OF T CELLS FOR NEXT-GENERATION CANCER IMMUNOTHERAPY: A MOLECULAR AND SYNTHETIC BIOLOGY PERSPECTIVE

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ABSTRACT

Cancer remains a major global health challenge, and despite recent advances in immunotherapy, current treatment strategies face significant limitations, particularly in solid tumors. Engineered immune cells—especially chimeric antigen receptor T cells (CAR-T)—have transformed hematological cancer therapy, yet issues such as antigen heterogeneity, inhibitory tumor microenvironments, therapy-related toxicities, and poor infiltration restrict broader clinical success. Recent developments in molecular engineering and synthetic biology now offer powerful tools to address these challenges, with CRISPR-mediated gene editing emerging as a crucial driver of enhanced precision, safety, and potency in engineered T-cell therapies. Current evidence shows that CRISPR knockout of inhibitory receptors such as PD-1 and LAG-3 increases T-cell persistence, while multiplex editing supports the development of universal allogeneic CAR-T cells capable of reducing graft-versus-host reactions. Similarly, synthetic gene circuits, logic-gated CAR constructs, engineered chemokine receptors, and cytokine rewiring strategies demonstrate improved tumor specificity, controlled activation, and enhanced infiltration into solid tumors. These findings align with rapidly growing research interests in programmable immune responses, metabolic reprogramming, and integration of computational modeling with multi-omics profiling to optimize gene-editing targets and engineering strategies. Based on reviewed advancements, recommended methodologies for future work include combining CRISPR-Cas9 systems with synthetic receptor design, employing 3D tumor spheroid models, microfluidic tumor chips, and in vivo CRISPR functional screens to evaluate engineered T-cell behavior under biologically relevant conditions. Overall, the convergence of molecular engineering and synthetic biology is enabling the creation of next-generation T-cell therapies capable of overcoming the long-standing barriers of solid tumor treatment, supporting their potential as safer, more precise, and highly customizable cancer immunotherapies.

Keywords: CAR-T cells, CRISPR-Cas9, synthetic biology, molecular engineering, tumor microenvironment, gene editing, immunotherapy, solid tumors, programmable immune cells, cancer therapy.

DATA-DRIVEN PREDICTIVE MAINTENANCE IN INDUSTRY 4.0: EVALUATION OF MACHINE LEARNING MODELS ON SYNTHETIC DATA

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ABSTRACT
In the context of Industry 4.0, it is essential to have an optimized system capable of detecting equipment failure in advance. For this purpose, Machine Learning models are used as decision-making approaches to address this challenge. Furthermore, a synthetic dataset was generated to validate these approaches. This dataset represents real-world industrial applications and provides data for prior estimation of machine failure based on several variables such as temperature, torque, rotational speed, and tool wear. Six Machine Learning models—Random Forest, XGBoost, Support Vector Classifier, K-Nearest Neighbors, Logistic Regression, and Multi-Layer Perceptron—were trained and compared based on their performance in predicting machine failures. The study shows that XGBoost achieved the highest accuracy of 98%, making it the most suitable model for predictive maintenance within the Industrial Internet of Things (IIoT) environment. Finally, this research demonstrates how synthetic data can enhance the development and validation of predictive maintenance solutions.
Keywords—Industrial IoT; Industry 4.0, predictive maintenance, Machine Learning

HIGH-RESOLUTION DROUGHT HOTSPOT MAPPING USING SENTINEL-BASED COMPOSITE INDICES

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ABSTRACT

Drought is a recurring climatic hazard that significantly affects agricultural productivity, water resources, and rural livelihoods in northern Bangladesh. This study assesses drought conditions exclusively in the Dinajpur, a district in northern Bangladesh using high-resolution remote sensing. This research applies high-resolution Sentinel-2 data to compute the Vegetation Condition Index (VCI) for detailed agricultural drought detection. Meteorological drought was evaluated using the Standardized Precipitation Index (SPI), while hydrological drought was assessed through the Standardized Water Level Index (SWI) using groundwater observations. A Composite Drought Index (CDI) was developed by integrating all three indicators. The Local Indicators of Spatial Autocorrelation (LISA) technique was used to identify drought hotspots and cold spots within Dinajpur at a finer spatial scale. The findings reveal more localized drought variability, enabling precise drought monitoring and supporting improved agricultural planning and drought-mitigation strategies for the district.

Keyword: Drought assessment, Vegetation Condition Index (VCI), Standardized Precipitation Index (SPI), Composite Drought Index (CDI), Remote sensing, Spatial analysis

MICROSTRUCTURAL, MICROBIOLOGICAL & PHYSICOCHEMICAL QUALITY OF DAIRY DESSERT CREAM AT DIFFERENT CONSERVATION TEMPERATURES

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ABSTRACT

This study evaluated the effect of storage temperature on the microbiological and physicochemical quality of a dairy dessert. The results showed that at 6 °C and 10 °C, the dessert remained stable and compliant with ISO standards, ensuring good shelf life and optimal food safety. In contrast, from 22 °C onwards, a rapid decrease in pH and an increase in acidity were observed, accompanied by the proliferation of pathogenic microorganisms such as Staphylococcus aureus and Enterobacteriaceae. Between 30 °C and 44 °C, spoilage accelerated due to microbial growth, increasing the risk of foodborne intoxications. Therefore, temperature appears to be the key factor determining product stability. Strict compliance with the cold chain, with a critical storage threshold set between 6 °C and 10 °C, is essential to guarantee the quality, safety, and regulatory compliance of the dairy dessert.

Keywords: Dairy dessert cream, Storage temperature, Microbiological quality, Physicochemical parameters, Cold chain, ISO standards.

MECHANICAL BEHAVIOURS OF SYMMETRIC UNIDIRECTIONNAL COMPOSITES LAMINATED E-GLASS/EPOXY

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ABSTRACT

The aim of our work is to characterize the elastic behavior of a unidirectional glass fiber reinforced composite laminate with a 60% volume fraction of epoxy resin matrix E. The determination of the elastic constants of the specifically orthotropic composite laminate is estimated using the rule of mixtures, and macro-mechanical studies have allowed us to determine the evolution of elastic constants based on fiber orientation and calculate the variation of thermo elastic quantities according to fiber orientation. Under the combined effect of mechanical stresses and temperature variations, the overall thermomechanical deformations of the unidirectional laminate will be determined by introducing longitudinal and transverse thermal expansions of the composite.

Keywords: Unidirectional composite laminate, thermo elastic behavior, fiber orientation

ESTIMATION OF THE STATE OF CHARGE AND HEALTH OF A LITHIUM-POLYMER BATTERY USING ULTRASONIC TECHNOLOGY

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ABSTRACT

The current era is characterized by the growing need for portable electronic systems, leading to a high demand for compact and efficient energy storage solutions. Lithium-ion batteries, particularly lithium-polymer (LiPo) cells, have emerged as a leading technology due to their high energy density and lightweight structure. However, their safe and optimal operation requires precise monitoring, typically ensured through a Battery Management System (BMS). This paper focuses on the non-destructive estimation of the State of Charge (SOC) and State of Health (SOH) of a LiPo cell using ultrasonic methods. After a detailed study of ultrasonic wave propagation and its interaction with electrochemical materials, an experimental protocol was developed to track changes in Time of Flight (TOF) and signal amplitude during battery discharge cycles. The results show a strong correlation between the acoustic parameters and the internal state of the cell, paving the way for a novel, non-invasive diagnostic technique that enables real-time monitoring without disturbing normal battery operation.

Keywords: LiPo Battery, SOC, SOH, Ultrasound, Time of Flight, Attenuation, Non-destructive method

DECARBONIZING OUR ENVIRONMENT: ADVANCING SUSTAINABLE DEVELOPMENT THROUGH POLICIES AND STRATEGIES

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ABSTRACT

Decarbonization is a pivotal strategy for combating climate change and achieving global sustainability objectives. This research paper explores the multifaceted approaches necessary to reduce carbon emissions across key sectors by harnessing cutting-edge technologies, maximizing energy efficiency, and driving the transition to renewable energy sources. The study highlights the critical role of decarbonization in justifying the adverse impact of climate change, global warming and ecological degradation while advancing sustainable development goals. Through a comprehensive analysis of technological advancements and policies, the paper identifies effective strategies and actionable solutions for minimizing carbon emissions. It emphasizes the importance of integrating support for policy, technological advancements, and teamwork to contribute to major decreases in carbon footprints. By examining best practices and recommending future research directions, this study seeks to add to the important global decarbonization conversation while promoting environmental stewardship. This paper serves as an important resource for policymakers, researchers, and stakeholders, providing insight into the attainment of a sustainable and resilient future through the implementation of comprehensive decarbonization policies and strategies.

Keywords: Decarbonization, Climate Change, Sustainability, Reducing Carbon Emissions, Greenhouse Gas Emissions, Environmental Degradation, Global Warming, Policy, Strategy, SDG, Resilience, Built-environment, Energy Efficiency, Sustainable Transportation, Transport Planning, Sustainable Industrialization.

REDUCING POST-HARVEST LOSSES: BOTANICAL CONTROL OF ANGOUMOIS GRAIN MOTH IN RICE

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ABSTRACT

The Angoumois grain moth (*Sitotroga cerealella*) poses a significant threat to stored grains, leading to considerable post-harvest losses on a global scale. This study evaluates the efficacy of six botanical treatments: *Codiaeum variegatum, Calendula officinalis, Allium sativum, Mentha piperita, Cymbopogon citratus*, and *Nephrolepis exaltata* against *S. cerealella* infestations in stored rice under controlled laboratory conditions. The experiment was carried out using a completely randomized design with six replications. The impact of the treatments on oviposition, egg hatching, larval mortality, pupal mortality, adult emergence, and percentage of damage was evaluated. The study shows that *Allium sativum* demonstrates superior effectiveness, achieving the highest pupal mortality rate (13.8%) and the lowest adult emergence (12.6%) compared to all other treatments. Notably, treatment with garlic resulted in an impressive 84% reduction in grain damage relative to the control, significantly outpacing the second most effective treatment, *Calendula officinalis*, which achieved a 61.5% reduction. These results underscore the potent insecticidal properties of garlic, attributed primarily to its active components, diallyl disulfide and diallyl trisulfide. The study compellingly supports the proposition that *Allium sativum* is a promising environmentally friendly alternative to conventional chemical pesticides for managing *S. cerealella* infestations in stored grains. This aligns with the growing demand for sustainable agricultural practices and food safety measures, positioning garlic as a viable solution to mitigate post-harvest losses in the grain storage sector.
Keywords: *Allium sativum*, botanical treatments, *Oryza sativa*, *Sitotroga cerealella*, stored grains, eco-friendly pest management.

INVESTIGATION OF THE THERMOELECTRIC PROPERTIES OF TWO-DIMENSIONAL JANUS MATERIALS

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ABSTRACT

First-principles calculations based on density functional theory (DFT) were carried out to explore the electronic and thermoelectric properties of 2H-phase molybdenum dichalcogenides MoQ_2 (Q = S, Se) along with their hypothetical mixed-layer heterostructure. Owing to the electronegativity contrast between sulfur (S) and selenium (Se), the formation of the mixed-layer $MoS_2/MoSe_2$ compound enables effective modulation of the electronic band structure. The results reveal that pristine MoS_2 and $MoSe_2$ possess indirect band gaps, whereas the mixed-layer $MoS_2/MoSe_2$ heterostructure exhibits a transition toward a pseudo-direct band gap, similar to the electronic behavior typically observed in monolayer MoQ_2 systems. This alteration in band-gap character has a marked impact on the electronic transport properties. Moreover, interlayer mixing significantly enhances the thermoelectric response by increasing the electronic density of states around the Fermi level and narrowing the band gap—two factors that promote higher carrier concentrations and lead to improved power factors. Overall, this study shows that layer mixing provides an efficient strategy for tailoring the electronic band structure of transition metal dichalcogenides and for optimizing their thermoelectric performance.

Keywords: MoS_2, $MoSe_2$, $MoS_2/MoSe_2$, Density functional theory (DFT), Electronic band gap, Thermoelectric properties.

EXTRACTION OF PECTIN BIOPOLYMER FROM JACKFRUIT PEEL: A REVIEW

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ABSTRACT
Jackfruit (Artocarpus heterophyllus) peel, a major agro-industrial residue, offers an underutilized yet promising source of pectin — a biodegradable polysaccharide valued for its gelling, stabilizing, and film-forming properties. This review compiles recent progress in the extraction, optimization, and characterization of pectin derived from jackfruit peel waste. Conventional acid extraction remains the most prevalent approach, typically using mineral or organic acids under temperatures of 80–95 °C and pH ranges between 1.5 and 2.5. Pretreatments such as convective drying and blanching substantially affect yield (5–16%) and quality parameters including degree of esterification and galacturonic acid content. Optimization through response surface methodology has further enhanced recovery, with yields reported up to 38%. In recent years, emerging green extraction technologies have shown superior efficiency and sustainability. Ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE) reduce processing time, improve diffusion, and yield high-quality low-methoxyl pectin with better antioxidant activity. Radio-frequency-assisted extraction (RFAE) has achieved even higher yields and degrees of esterification, suggesting potential for high-methoxyl pectin production. These innovative methods minimize chemical consumption and energy use while preserving functional integrity. Overall, extraction parameters such as acid concentration, pH, temperature, pretreatment, and technique strongly influence pectin yield and composition. Transitioning toward eco-friendly, energy-efficient extraction supports sustainable utilization of jackfruit peel waste. Jackfruit peel thus emerges as a renewable source for pectin biopolymer production, offering broad applications in food, pharmaceuticals, and biodegradable materials. Keywords: Jackfruit peel, pectin, acid extraction, ultrasound, microwave, radio frequency, biopolymer.

FEASIBILITY OF USING RICE STRAW BALE AS A WALLING MATERIAL FOR SUSTAINABLE AND AFFORDABLE LOW INCOME MASS HOUSING IN GOMBE METROPOLIS, NIGERIA

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ABSTRACT

The escalation in the cost of conventional construction materials, compounded by prolonged insurgency in North Eastern Nigeria, has significantly exacerbated the housing scarcity prevalent in Gombe State. Factors influencing housing deficit in the region include rapid population growth, urbanization, migration from neighbouring states affected by insurgency, and insufficient investment in the housing sector. The building industry consumes approximately 40% of the world's total energy which is unsustainable. Straw bale as a sustainable and affordable material is therefore considered as an ideal building *material* because of its renewable nature and low environmental impact with a rich history of utilization in North America, Europe and Asia. Although it remains largely underutilized in Nigeria, often disposed by open burning which exacerbates to the challenges of climate change in the built environment. Gombe State, emerging as a significant player in the rice production industry with an annual production capacity of over 140,107 metric tonnes, stands to leverage rice straw bale as a construction material, which would enhance housing sustainability and affordability within the region. Qualitative research approach was adopted for this study and data were collected through face to face interview. Thematic analysis was adopted to interpret the data, from the findings. 25 persons across the three categories of the participants (Civil Servants, Farmers and Professionals in the building industry) are of the opinion that straw bale is an affordable building material than conventional building material with 4 participants having the opinion of choosing conventional building materials to be more affordable and more accessible than straw bale, while 1 person did not make comment. This research also found 19 out of the 30 interviewees are of the opinion of building with straw bale as a walling material stating reasons such as: local material availability, sustainability, insulation, cost savings, and potential economic development as the major benefits of using straw bale as a construction material. However, concerns for inadequate awareness, scarcity of skilled professionals and artisans, funding constraints, susceptibility to termite infestation, fire rating, durability, public

acceptance, weather resistance, adherence to building codes, and aesthetic considerations were identified as challenges for the adoption and application of straw bale. In conclusion, this research suggest the treating the straw bales using sodium borate also known as borax powder or used engine oil to prevent termite infestations, mixing of breathable stucco such as clay with lime in plastering to assist in achieving indoor air quality (IAQ) and prevention of plant sprout from the bales, organising multi-media workshops, trainings and issuing certification such as Breeam, Leeds can also aid in creating public awareness on using straw bale as a walling material. Additionally, involvement of private sector stakeholders, estate developers, policy makers and robust research efforts on affordability, applicability and sustainability of straw bale is emphasized.

Keywords: Climate Change, Indoor air quality, Sustainable building material, Straw bale

UNMASKING THE MARGINS: A BIBLIOMETRIC ANALYSIS OF GEOGRAPHICAL BIAS IN AFROCENTRIC ARCHITECTURAL RESEARCH AND PATHWAYS TO PAN-AFRICAN EQUITY

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ABSTRACT

Afrocentric architecture represents a decolonial paradigm that centers African cultural, spiritual, and environmental principles in contemporary design, countering Eurocentric dominance in architectural theory and practice. Rooted in Afrocentricity, it emphasizes indigenous technologies, climatic responsiveness, and cultural symbolism to foster sustainable, context-sensitive built environments. Despite its promise for epistemic reclamation and pan-African unity, the field is plagued by profound geographical imbalances, with research predominantly concentrated in West and Southern Africa due to established academic infrastructures, colonial legacies, and funding disparities. This bias fragments the discourse, neglecting vibrant traditions in Central, East, and North Africa, such as Nubian vaults, Swahili coral-stone houses, and Congolese earth structures, thereby limiting a comprehensive continental framework. This study addresses this critical gap through a PRISMA-guided systematic literature review and bibliometric analysis of Afrocentric architectural research from 2015 to 2025. Using Google Scholar, a Boolean search strategy identified 20,306 initial articles, refined to 139 relevant peer-reviewed publications based on inclusion criteria focusing on English-language studies in built environment fields with geographical context. Data extraction included authorship, affiliations, countries of origin, and publication trends, analyzed via network mapping and density visualizations to quantify regional representation. Results reveal a stark West/South dominance, with West Africa contributing 55 outputs (e.g., Nigeria: 42) and Southern Africa 53 (e.g., South Africa: 51), while East Africa (12), Central Africa (2), and North Africa (1) remain severely underrepresented. Diaspora contributions (16) from the U.S.,

U.K., and Europe underscore external epistemic influence. Publication trends peaked at 26 in 2020, reflecting growing decolonial interest, but declined thereafter, highlighting data limitations and uneven methodological approaches across regions. These findings expose structural inequalities that hinder theoretical integration, sustainability discourse, and architectural education, perpetuating epistemic injustice. By mapping biases, the study advocates for equitable interventions to achieve a truly inclusive Afrocentric paradigm. Recommendations include multilingual bibliometric databases, intra-African collaborations, open-access platforms, targeted funding for underrepresented regions, and curriculum diversification to incorporate diverse case studies. Ultimately, addressing geographical bias is essential for redefining Afrocentric architecture as a unified, representative continental narrative that honors Africa's full cultural and environmental spectrum.

Keywords: Afrocentric architecture, geographical bias, bibliometric analysis, decolonization, epistemic equity

DFT-GUIDED ANALYSIS OF REGIO- AND STEREOSELECTIVITY IN THE HYDROBORATION-OXIDATION OF A-TRANS-HIMACHALENE

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ABSTRACT

This study reports the successful synthesis of a sesquiterpenic alcohol ($C_{15}H_{26}O$) via the hydroboration–oxidation of (R)-α-trans-himachalene using 9-borabicyclo[3.3.1]nonane (9-BBN) followed by oxidative workup with H_2O_2/OH^- in tetrahydrofuran. The chemoselectivity of this transformation was investigated through a combined experimental and theoretical approach. Density Functional Theory (DFT)-based Molecular Electron Density Theory (MEDT) analyses, including Parr's electrophilicity and nucleophilicity indices, electron

localization function (ELF) topological studies, and activation energy calculations, were employed to rationalize the observed regioselectivity. Theoretical predictions aligned well with experimental outcomes, confirming preferential attack at the less substituted double bond of α-trans-himachalene. Notably, solvent effect studies revealed significantly lower activation barriers in water and ethanol compared to traditional organic solvents, highlighting the feasibility of conducting this reaction under greener, more sustainable conditions. Mechanistic insights indicate a concerted yet asynchronous hydroboration pathway, characterized by uneven bond formation during the transition state. Furthermore, molecular docking simulations were performed to evaluate the potential biological activity of the synthesized alcohol isomers (P"1 and P"2). Docking against human Topoisomerase II (PDB: 1ZXM) and Tubulin (PDB: 1SA0)—using etoposide and paclitaxel as reference inhibitors—demonstrated promising binding affinities and interaction profiles. These results suggest that the derived alcohols warrant further investigation as potential anticancer agents.

Keywords: hydroboration-oxidation, MEDT, ELF, α-trans-himachalene, activation energy.

DESIGN OF AN ARTIFICIAL NEURAL NETWORK-BASED DECISION SUPPORT SYSTEM FOR FORENSIC INFORMATICS APPLICATIONS

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ABSTRACT

One of the major factors that profoundly disrupt historical and social order is the phenomenon of terrorism. Terrorist acts not only result in loss of life but also place significant strain on countries' economic resources, infrastructure investments, and security budgets. Therefore, counterterrorism has become one of the core components of national security policies for many states. On the other hand, rapid advancements in information technologies have enabled the use of applications capable of supporting decision-making processes and generating future predictions across various fields such as health, economy, security, and intelligence. In this study, an artificial neural network–based classification model was designed using the Global Terrorism Database to predict which organization may have carried out a given terrorist attack and to support the deepening of the investigation process in this direction. To ensure the model is reliable and applicable, steps such as data preprocessing, appropriate feature selection, and parameter optimization were carried out meticulously. Thus, the raw information in the sample dataset was processed and transformed into meaningful outputs that security analysts can utilize in their evaluations, enabling event-based predictions to be made. An examination of the findings obtained from the artificial neural network models shows that the algorithm is a usable and effective method for the relevant classification problem when considering its accuracy level and processing times. To evaluate the performance of the developed ANN models, the system was executed, and a confusion matrix along with the performance metrics derived from it was calculated based on the obtained outputs. The results of these evaluations are presented in tabular form.

Dimensionality Reduction	Cross-Validation	Number Variables	of Accuracy (%)	Standard Deviation (%)
No	No	13	93.61	0.15
No	Yes	7	95.23	0.29
Yes	No	4	93.38	0.35
Yes	Yes	3	93.57	0.27

Keywords: Forensic Informatics, Artificial Neural Networks, Classification

DERİN ÖĞRENME YÖNTEMLERİ İLE ERKEN FÜZYON TABANLI ÇOK MODLU DUYGU ANALİZİ

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ÖZET

Çok modlu duygu analizi; metin, ses ve görüntü gibi farklı veri türlerinin birlikte değerlendirilmesiyle duyguların daha kapsamlı ve gerçekçi bir şekilde incelenmesini sağlayan bir yaklaşımdır. Metin verilerinde dilbilgisi yapısı ve kelime seçimi; ses verilerinde tonlama, vurgu ve ses perdesi; görsel verilerde yüz ifadeleri ve mimikler duygu durumunu anlamada önemli ipuçları sunmaktadır. Bu yöntem günümüzde sosyal medya analizinden sağlık, hukuk, eğitim ve pazarlama gibi birçok alanda yaygın olarak kullanılmaktadır. Bu çalışmada metin ve ses verileri birlikte ele alınarak çok modlu bir duygu analizi modeli geliştirilmiştir. Ses verilerinden Mel-Frequency Cepstral Coefficients (MFCC) ve mel-spektrogram tabanlı özellik çıkarımı yapılmış ve bu temsiller Convolutional Neural Network (CNN) tabanlı modeller aracılığıyla işlenmiştir. Metin verilerindeki anlamsal ve zamansal ilişkiler ise Long Short-Term Memory (LSTM) tabanlı model ile temsil edilmiştir. Erken füzyon yaklaşımı benimsenerek her iki moddan elde edilen temsil vektörleri sınıflandırma aşamasında birleştirilmiş ve bu doğrultuda çok modlu bir mimari oluşturulmuştur. Çalışmada MELD veri seti kullanılmış olup tek modlu (yalnızca metin veya yalnızca ses) yapılar ile çok modlu yapı karşılaştırılmıştır. Elde edilen sonuçlar, metin ve ses verilerinin ayrı ayrı işlendiği durumlara kıyasla çok modlu yapının daha dengeli bir performans ortaya koyabildiğini göstermektedir. Bununla birlikte, RoBERTa–BiLSTM tabanlı metin modeli ile MFCC+CNN2D ses modelinin erken füzyonla birleştirilmesinin, hem üç duygu sınıfında (pozitif, negatif, nötr) hem de yedi sınıflı duygu (öfke, tiksinti, korku, neşe, nötr, üzüntü, şaşkınlık) analizinde performansa olumlu yönde katkı sunduğu gözlemlenmiştir. Bu bulgular, erken füzyonlu çok modlu yaklaşımların duygu sınıflandırma çalışmalarında tek modlu yöntemlere göre daha bütüncül ve etkili bir değerlendirme imkanı sunduğunu ortaya koymaktadır.

Anahtar Kelimeler: Çok Modlu Duygu Analizi, Erken Füzyon, Doğal Dil İşleme (NLP), MFCC, CNN, LSTM

MULTIMODAL EMOTION ANALYSIS BASED ON EARLY FUSION USING DEEP LEARNING METHODS

ABSTRACT

Multimodal emotion analysis is an approach that enables a more comprehensive and realistic examination of emotions by jointly evaluating different types of data, such as text, audio, and visual inputs. In text data, grammar structure and word choice; in audio data, intonation, stress, and pitch; and in visual data, facial expressions and gestures provide important clues for understanding emotional states. This method is widely used today in many fields, from social media analysis to healthcare, law, education, and marketing. In this study, a multimodal emotion analysis model was developed by considering text and audio data together. Features were extracted from audio data based on Mel-Frequency Cepstral Coefficients (MFCC) and mel-spectrograms, and these representations were processed using Convolutional Neural Network (CNN)-based models. Semantic and temporal relationships in text data were represented using a Long Short-Term Memory (LSTM)-based model. An early fusion approach was adopted, combining the representation vectors obtained from both modalities during the classification stage, thereby creating a multimodal architecture. The MELD dataset was used in the study, and single-modal (text-only or audio-only) structures were compared with the multimodal structure. The results obtained show that the multimodal structure can deliver a more balanced performance compared to cases where text and audio data are processed separately. In addition, combining the RoBERTa–BiLSTM-based text model with the MFCC+CNN2D audio model through early fusion was observed to contribute positively to performance in both three emotion classes (positive, negative, neutral) and seven-class emotion (anger, disgust, fear, joy, neutral, sadness, surprise) analysis. These findings reveal that early fusion multimodal approaches offer a more comprehensive and effective evaluation opportunity in emotion classification studies compared to single-modal methods.

Keywords: Multimodal Emotion Analysis, Early Fusion, Natural Language Processing (NLP), MFCC, CNN, LSTM

EXPLORING COOPERATION IN ASYMMETRIC DYADIC GAMES THROUGH SPATIAL MONTE CARLO SIMULATIONS AND NETWORK STRUCTURES

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ABSTRACT

Understanding the emergence and stability of cooperation in asymmetric social interactions remains a central challenge in evolutionary game theory. In this study, we develop a two-population asymmetric dyadic game model incorporating heterogeneity in behavioral traits, including risk aversion and gambling tendencies, alongside an asymmetric payoff-sharing mechanism. Using both analytical derivations and Monte Carlo based spatial simulations, we investigate how localized interactions drive the evolution of strategies across different initial spatial configurations. In particular, we explore three distinct setups random, box, and circular clusters to examine how strategy update dynamics unfold under identical Fermi update rules. We further analyze how variations in neighborhood size and the use of different network topologies influence the spread and stabilization of strategies. Our results demonstrate that the spatial organization of initial strategies profoundly affects the formation and persistence of cooperative clusters, defective regions, and asymmetric strategy pairings. Clustered configurations promote more robust cooperation, whereas random arrangements are more susceptible to stochastic extinction. Moreover, increasing node degree or adopting alternative network structures, such as small-world or scale-free topologies, modifies local interactions and can enhance the resilience of cooperation. These findings highlight the intricate interplay between behavioral heterogeneity, structural asymmetry, spatial context, and network topology, providing insights into the promotion of cooperation in socio-economic systems characterized by diversity and inequality.

Keywords: Evolutionary Game Theory; Monte Carlo; Network Topology

OPTIMIZING AGRICULTURAL SUSTAINABILITY THROUGH ARTIFICIAL INTELLIGENCE AND BIG DATA

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ABSTRACT

Artificial intelligence (AI) and Big Data are playing an increasingly important role in optimizing agricultural sustainability by addressing challenges related to productivity, natural resource management, and adaptation to climate change. Thanks to advanced algorithms, AI enables the analysis of massive volumes of data from sensors, satellites, and weather stations. These analyses promote precision agriculture, where decisions are based on accurate forecasts, thereby reducing the waste of inputs (water, fertilizers, pesticides) and optimizing yields. In terms of resource management, Big Data allows for real-time monitoring of soil and crop conditions, promoting efficient irrigation and targeted fertilization. This approach contributes to the preservation of ecosystems while enhancing the resilience of farms to climate-related risks. For example, AI can predict periods of drought or the emergence of diseases, enabling farmers to anticipate necessary interventions. However, several challenges hinder the adoption of these technologies. On the technical front, data interoperability remains a major obstacle, as platforms and tools need to be compatible with one another. Economically, the implementation costs of AI and Big Data technologies can be prohibitive for many farmers. Socially, their acceptance depends on the training and awareness of farmers. Finally, the environmental impact of digital infrastructure (servers, energy consumption) must be taken into account to avoid an environmental paradox. Thus, to fully leverage AI and Big Data in sustainable agriculture, an integrated approach is necessary, combining technological innovation, economic accessibility, and awareness-raising among sector stakeholders.

Keywords: AI, Agriculture, Big data, Deep learning, Model.

MICROBIAL FUEL CELL-DRIVEN EVALUATION OF EXOELECTROGEN FROM MUNICIPAL WASTEWATER FOR ELECTRICITY GENERATION AND BIOREMEDIATION

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ABSTRACT

With the growing global concern over energy sustainability, microbial fuel cells (MFCs) have gained attention as a promising green technology for generating bioelectricity from biodegradable waste using bacteria. MFCs offer a powerful two-in-one solution, bioelectricity production and environmental bioremediation, making them a promising path toward a more sustainable future. The aim of this study is to use MFC to search for bioelectricity-producing bacteria from municipal wastewater to evaluate the isolate's potential in organic waste bioremediation. A duel-chambered MFC was constructed using an anode, a cathode, and Proton exchange membrane to detect the presence of exoelectrogenic bacteria. Initial detection of exoelectrogenic activity was monitored through voltage and current output measured by using a multimeter. Anode biofilm bacteria were selectively cultured on MnO_2-supplemented minimal media for 16 to 24 hours in anaerobic condition to distinguish exoelectrogens based on their ability to solubilize MnO_2 and milk-white colony formation. A second MFC was set up with the isolated strain to evaluate its electricity-generating capability. Biochemical tests and 16S rRNA sequencing were performed for identification. Furthermore, the isolate's potential in organic waste bioremediation was evaluated. The initial MFC system inoculated with mixed biofilm bacteria from municipal wastewater generated 0.22 V and 0.14 mA. After 16–24 hours, MnO_2-supplemented minimal media developed milk-white colonies, indicating exoelectrogenic bacteria solubilize MnO_2, using it as a terminal electron acceptor. Uninoculated areas remained black due to unutilized MnO_2. The second MFC, inoculated with isolated strains, showed improved outputs of 0.544 V and 0.18 mA. Biochemical tests and 16S rRNA sequencing identified *Staphylococcus capitis*. Enzymatic assays confirmed the isolate's ability to degrade protein, cellulose and lipid in organic waste. Our isolated bacteria have the capability to degrade organic waste and produce electricity as byproduct.

Keywords: Microbial fuel cell, Exoelectrogenic bacteria, Bioelectricity, Bioremediation, Green technology.

METRO İSTASYONLARINDA YANGIN GÜVENLİĞİNİN YAYA SİMÜLASYONU İLE ANALİZ EDİLMESİ VE TASARIM ÖNERİLERİ

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ÖZET

Büyükşehirlerde ve yüksek nüfus yoğunluğuna sahip kentlerde toplu taşımaya olan talebin her geçen gün artması, etkin, sürdürülebilir ve kullanıcı odaklı toplu taşıma sistemlerinin planlanması ve uygulanmasının zorunlu hale gelmesine neden olmaktadır. Özellikle yoğun nüfuslu kentlerde yaşanan trafik sıkışıklıkları, lastik tekerlekli toplu taşıma araçlarının seyahat sürelerini uzatmakta, seyahat konforunu düşürmekte ve bu sistemlerin kullanıcılar tarafından tercih edilme olasılığını azaltmaktadır. Bu bağlamda, yüksek kapasiteye sahip, daha hızlı ve daha az trafik etkisine maruz kalan metro sistemleri, kent içi ulaşımın temel bileşenleri olarak öne çıkmaktadır. Metro sistemleri, yoğun yolcu hareketlerini güvenli ve verimli bir şekilde yönetebilme potansiyeline sahip olup, kentlerin ulaşım altyapısında önemli bir rol oynamaktadır. Metro istasyonları, yoğun yolcu hareketinin yaşandığı ve karmaşık sirkülasyonların meydana geldiği alanlardır. Bu nedenle, kullanıcıların güvenli, konforlu ve hızlı bir şekilde hareket edebilmelerini sağlayacak şekilde tasarlanmaları büyük önem taşımaktadır. Özellikle yeraltında inşa edilen metro istasyonlarında, giriş-çıkış noktalarının sınırlı olması nedeniyle, olası bir acil durumda tahliye süreci zorlaşmaktadır. Bu tür durumlarda, yolcuların en kısa sürede ve düzenli bir şekilde tahliye edilmesi hem can güvenliği hem de sistem güvenilirliği açısından kritik bir öneme sahiptir. Bu nedenle, metro istasyonları projelendirilirken acil durum senaryolarının dikkate alınması büyük önem arz etmektedir. Bu çalışmada, bir metro istasyonunda yaşanan yolcu hareketleri, yaya simülasyonu yazılımı kullanılarak üç boyutlu ortamda detaylı bir şekilde modellenmiş ve yangın tahliye senaryoları simüle edilmiştir. Simülasyonlar sonucunda, tahliye süreleri, gecikme yaşanan noktalar ve darboğaz bölgeleri analiz edilmiştir. Elde edilen veriler, hizmet düzeyi kriterleri ve uluslararası tasarım standartlarıyla ilişkilendirilerek, istasyonun mevcut performansı değerlendirilmiştir. Tespit edilen sorunlar için mimari tasarım değişikliğine gidilerek çözüm önerileri geliştirilmiş ve yaya simülasyonu teknolojisi aracılığıyla tasarım önerilerinin etkisi ölçülmüştür. Böylece, metro istasyonu tasarımlarının iyileştirilmesi sürecinde yaya simülasyonunun sağladığı avantajlar ortaya konulmuştur.

Anahtar Kelimeler: Metro İstasyonu, Acil Durum Tahliyesi, Modelleme, Yaya Simülasyonu

ANALYSIS OF FIRE SAFETY IN METRO STATIONS USING PEDESTRIAN SIMULATION AND DESIGN RECOMMENDATIONS

ABSTRACT

The continuous increase in demand for public transportation in metropolitan areas and cities with high population density has made it essential to plan and implement effective, sustainable, and user-oriented public transportation systems. In particular, traffic congestion in densely populated cities extends the travel times of rubber-tired public transport vehicles, reduces travel comfort, and decreases the likelihood of these systems being preferred by users. In this context, metro systems, which have high capacity, are faster, and are less affected by road traffic, emerge as fundamental components of urban transportation. Metro systems possess the potential to manage intense passenger movements safely and efficiently, playing a significant role in the transportation infrastructure of cities. Metro stations are spaces where intense passenger movements and complex circulations occur. Therefore, it is crucial that they are designed to allow users to move safely, comfortably, and quickly. Especially in underground metro stations, the limited number of entry and exit points makes evacuation processes more challenging in case of an emergency. In such scenarios, the rapid and orderly evacuation of passengers is critical for both life safety and system reliability. For this reason, it is highly important that emergency scenarios are considered during the design phase of metro stations. In this study, passenger movements in a metro station were modeled in detail in a three-dimensional environment using pedestrian simulation software, and fire evacuation scenarios were simulated. Based on the simulation results, evacuation times, points of delay, and bottleneck areas were analyzed. The obtained data were evaluated by associating them with service level criteria and international design standards to assess the current performance of the station. For the identified problems, solution proposals were developed through architectural design changes, and the impact of these design proposals was measured using pedestrian simulation technology. Thus, the advantages provided by pedestrian simulation in the process of improving metro station designs were revealed..

Keywords: Metro Station, Emergency Evacuation, Modeling, Pedestrian Simulation

SENTIMENT ANALYSIS OF PUBLIC OPINION TEXTS BASED ON LARGE LANGUAGE MODEL

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ABSTRACT

Sentiment analysis, which involves identifying and categorizing emotions in textual data, has advanced significantly with the development of large language models (LLMs). This research focuses on optimizing sentiment analysis techniques for public opinion texts using LLMs, specifically evaluating models with 7 billion parameters, such as Qwen-7B, ChatGLM2-6B, and Aquila-7B. The study assesses their performance in tasks like emotion detection, humor recognition, and metaphor identification across seven datasets, providing insights into their ability to handle various sentiment analysis tasks. To further enhance model performance, the research introduces optimization techniques, including prompt optimization to refine task understanding and fine-tuning using methods like LoRA and P-Tuning to improve sentiment analysis accuracy. The innovative aspects of this research are the evaluation of smaller-scale LLMs for sentiment analysis, alongside the exploration of prompt-based optimization and efficient fine-tuning methods. By enhancing these models, the research contributes to more effective sentiment analysis in public opinion mining, which has significant implications for businesses, governments, and society. The ultimate goal is to establish a robust sentiment analysis framework for LLMs, leading to a comprehensive academic paper and potentially a patent submission.

Keywords: Sentiment Analysis, Large Language Models (LLMs), Public Opinion Mining.

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ABSTRACT

In today's digital era, vast amounts of video data are generated across platforms like YouTube, Instagram, and educational portals. Manually analyzing this content is slow, inefficient, and unstructured compared to text. To address this, the Video Analyzer project proposes an AI-driven framework that automatically understands, summarizes, and interprets videos in real time. The system combines Computer Vision (CV), Automatic Speech Recognition (ASR), and Natural Language Processing (NLP) to analyze visual, audio, and contextual information. Using deep learning models such as CNNs, RNNs, and Transformers, it can detect objects, recognize activities, convert speech to text, and produce high-level semantic summaries—moving from basic detection to comprehensive video understanding. Designed for real-time analytics, the solution supports applications in surveillance, healthcare, education, sports, and assistive technologies. It requires high-performance CPUs/GPUs along with frameworks like TensorFlow, PyTorch, OpenCV, and Hugging Face models. Ultimately, the Video Analyzer makes video content more accessible, automated, and insightful, bridging the gap between raw video data and actionable knowledge. performs sentiment analysis and generates a concise summary of the content. The Video Analyzer reduces manual effort, improves accuracy, and provides a comprehensive understanding of video material through an interactive and user-friendly interface. This system is useful for creators, researchers, and users who need quick and reliable video insights.

Keywords: Video Summarization, Video Interpretation, Multimodal analysis, AI-driven framework, Deeplearning, Artifical Intelligence, Computer Vision (CV), Natural Language Processing (NLP), Generative AI, Python, OpenAI Whisper, Object detection, Activity recognition, Context extraction, Surveillance, Healthcare, Video-based search, Automation, Efficiency, Human-like interpretation, Real-time processing, Digital era, AI integration, Human-computer interaction.

DESIGN OF A BROADBAND S-BAND MICROSTRIP ANTENNA WITH MODIFIED GROUND GEOMETRY FOR BIOSYSTEMS AND MARITIME RADAR APPLICATIONS

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ABSTRACT

The increasing dependence on maritime and coastal resources for fisheries, aquaculture, agricultural logistics, and environmental monitoring has intensified the need for compact and efficient radar technologies capable of supporting modern agricultural and biosystems engineering applications. This study presents a novel S-band (2–4 GHz) rectangular microstrip antenna designed to enhance the performance of maritime radar systems used in coastal crop transport management, fishery surveillance, maritime safety, and remote environmental monitoring. The antenna integrates a serrated and perforated ground plane structure to overcome the traditional bandwidth–size limitations of microstrip designs. Implemented on a cost-effective FR4 substrate (ε_r = 4.3, h = 1.3 mm, tanδ = 0.025), the antenna maintains a compact physical size of 0.31λ × 0.31λ × 0.01λ and employs a 50-Ω inset feed for stable excitation. Simulations conducted using CST Microwave Studio Suite (2024) demonstrate excellent performance, achieving an S_{11} of –60.78 dB, a bandwidth of 1.605 GHz (2.054–3.659

GHz), 83.77% radiation efficiency, 1.76 dBi gain, and 2.53 dBi directivity. Experimental validation using CNC3-3018Pro fabrication and a LiteVNA™-64 measurement system produced closely aligned results, with a measured S_{11} of –59.60 dB at 2.28 GHz and a bandwidth of 1.505 GHz. Minor discrepancies are attributed to fabrication tolerances. The high bandwidth and efficiency of the proposed antenna make it suitable for agricultural radar applications including vessel-based crop transport monitoring, environmental sensing, livestock tracking near coastal areas, and integration into autonomous biosystems platforms. Future work will focus on improved gain enhancement, hybrid substrate optimization, and multi-band operation for expanded agricultural and environmental monitoring capabilities.

Keywords: Maritime Radar, Agricultural Monitoring, Microstrip Antenna, Serrated Ground Plane, Biosystems Engineering.

BUG WHISPERER-ERROR EMOTION MAPPING

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ABSTRACT

Bug Whisperer is an intelligent learning companion designed to bridge coding errors and emotional responses. The system continuously monitors a programmer's workflow, capturing errors from executed code alongside real-time emotional signals gathered through webcam analysis and keystroke dynamics. Each error event is stored with its corresponding affective state to compute a personalized frustration score. Over time, Bug Whisperer generates a visual "frustration map" that highlights which error types trigger the most stress. This map not only reveals emotional bottlenecks but also drives targeted recommendations of learning resources, helping developers strengthen weak concepts. By integrating error tracking, affective computing, and adaptive feedback, Bug Whisperer personalizes programming education, turning frustration into actionable guidance and enhancing both skill development and learner resilience.

Keywords: Facial Emotion Recognition, Keystroke Dynamics, Frustration Score, Affective Computing, Error Monitoring, Personalized Learning, Heatmap Visualization, Cognitive Load, Human-Computer Interaction, Real-Time Analysis, Emotional Feedback, Programming Education, Behavior Tracking, Adaptive Learning, Machine Learning Model, User Experience Enhancement, Stress Detection, Educational Technology.

COMPOSITION AND EMERGING APPLICATIONS OF *ZINGIBER OFFICINALE* ESSENTIAL OIL

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ABSTRACT

Zingiber officinale (ginger) essential oil is of growing scientific and industrial interest due to its rich phytochemical composition and notable biological activities. This abstract highlights key constituents—including zingiberene, β-bisabolene, and zingiberol—and their roles in antimicrobial, antioxidant, and anti-inflammatory functions. Advances in extraction techniques, such as optimized steam distillation and green extraction methods, have improved oil yield and bioefficacy. Recent studies support the oil's potential in reducing oxidative stress, inhibiting pathogenic microbes, and contributing to natural preservative and pharmaceutical applications. As demand for plant-derived bioactives increases, understanding compositional variability linked to cultivar type, geographic origin, and post-harvest handling is essential. Future opportunities include standardization, sustainability-focused production, and further translational research to expand the therapeutic and commercial use of ginger essential oil.

Keywords: Ginger Essential Oil, *Zingiber officinale*, Phytochemicals; Antimicrobial Activity, Antioxidant Activity

THE *IN-VITRO* EVALUATION OF THE ANTI-INFLAMMATORY ACTIVITY OF *OLEA EUROPAEA* L. LEAVES EXTRACT

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ABSTRACT

Protein denaturation was identifiend as a key factor of the development of inflammation, and inhibiting this factor is a primordial mechanim for the intiinflammatory substances. In this context, the present study aims to evaluate the anti inflammatory activity of *Olea europaea* L. leaves extract *in vitro* by assessing its ability to inhibit protein denaturation. The *in vitro* assay was performed by testing the *Olea europaea* L extract against denaturation of Bovine Serum Albumin (BSA) and egg albumin flakes (ovalbumin). The extract was prepared using hydromethanolic (85%) extraction and tested at increasing concentrations ranging from 100 to 800 µg/mL. The diclofenac sodium a synthetic non-steroidal anti-inflammatory drug was assayed in similar experimental conditions as a positive control. The findings demonstrated that *Olea europaea* L. leaves extract exhibited particularly high efficacy at 800 µg/mL, reaching an inhibition percentage of 81.59% by BSA test and 75.18% by ovalbumin test which suggests a strong protective activity against thermal protein denaturation. Conversely, diclofenac sodium exhibited an percentage inhibition of 67. 36% at 800 µg/mL. These findings suggest that the anti-denaturation effect of olive leaves extract is comparable to, and in some cases more potent than, that of diclofenac sodium. This results suggests that *Olea europaea* L leaves extract possesses a significant anti-inflammatory properties, which may be attributed to its rich phenolic composition such as oleuropein and it can be used as a promising natural alternative to anti-inflammatory synthetic drugs.

Keywords: antiinflamatory activity, *in vitro*, *Olea europaea* L., hydro-methanolic extract.

GHMYB44 ORCHESTRATES A MULTI-TIERED CASCADE TO REGULATE SECONDARY CELL WALL BIOSYNTHESIS IN COTTON FIBERS

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ABSTRACT

Secondary cell wall (SCW) formation is essential for generating the mechanical strength and structural integrity of specialized plant cells. Cotton fibers provide an excellent single-cell model for dissecting the regulatory mechanisms underlying massive cellulose deposition. However, how upstream transcription factors coordinate the sequential activation of SCW biosynthetic genes remains incompletely understood. In this study, we identify GhMYB44, an R2R3-MYB transcription factor, as a central regulator orchestrating a multi-tiered transcriptional cascade controlling SCW biosynthesis in cotton fibers. Functional analyses demonstrate that GhMYB44 acts as a positive regulator of SCW formation and directly activates the NAC-domain transcription factor GhFSN43, a key determinant of cellulose synthesis. GhFSN43 subsequently induces major cellulose synthase genes, establishing a complete regulatory module from an upstream MYB to

downstream structural genes. We further uncover two critical protein–protein interaction nodes that amplify transcriptional output within this pathway. GhMYB44 forms a complex with the HD-ZIP III protein GhREV5, enhancing the initial transcriptional activation of GhFSN43. At the downstream level, GhFSN43 cooperates with GhFSN1 to strengthen activation of cellulose biosynthetic genes. These synergistic interactions ensure robust and efficient SCW deposition during fiber development. Together, our findings reveal a multi-layered regulatory network in which transcriptional control is reinforced through hierarchical TF–TF interactions. This work provides new mechanistic insight into SCW biosynthesis and identifies promising molecular targets for improving cotton fiber quality and performance.

Keywords: cotton fiber, secondary cell wall, transcription factor, GhMYB44, GhFSN43, cellulose biosynthesis

GROWTH ASSESSMENT AND ECONOMIC INDICES OF *CLARIAS GARIEPINUS* CULTURED IN A CLARIAS-DUCKWEED AQUAPONICS SYSTEM

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ABSTRACT

This study investigated the use of duckweed as a sustainable and cost-effective alternative feed for *Clarias gariepinus* in an aquaponic system. The primary objective was to assess the growth performance and economic viability of incorporating duckweed into the fish diet. A Completely Randomized Design (CRD) was employed with five dietary treatments (DT) where duckweed replaced commercial feed at 0% (DT I, control), 25% (DT II), 50% (DT III), 75% (DT IV), and 100% (DT V). One hundred fingerlings were distributed into five tanks (20 fish per tank) and fed twice daily at 5% body weight for four weeks. Growth parameters, feed utilization, and economic indices were monitored. Results indicated that the 50% duckweed inclusion level (DT III) yielded the best growth performance, with a significantly higher ($P<0.05$) mean final weight (75.97 g), specific growth rate (3.43%/day), and the best feed conversion ratio (1.28). Diets with higher duckweed inclusion (DT IV and DT V) resulted in significantly poorer growth and feed efficiency. Proximate composition of the fish flesh showed that higher duckweed inclusion increased crude protein content. Economically, despite a higher feed cost, DT III generated the highest gross revenue (₦3,038.67), net profit (₦2,968.16), and cost-benefit ratio (43.11), demonstrating superior profitability. The study concludes that duckweed can effectively replace up to 50% of commercial feed in the diet of *Clarias gariepinus* without compromising growth, while significantly enhancing economic returns. It is recommended that farmers adopt this moderate inclusion level to reduce production costs and improve the sustainability and profitability of *Clarias*-duckweed aquaponics systems.

Keywords: Aquaponics, *Clarias gariepinus*, Duckweed, growth assessment, Economic indices, Sustainable Aquaculture.

BACTERIOLOGICAL ASSESSMENT OF MOUSSA STREAM IN BIDA, NIGER STATE, NIGERIA

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ABSTRACT

The study assessed the bacteriological quality of Moussa Stream in Bida, Niger State, Nigeria, Water samples were collected from three different locations and cultured on Nutrient Agar (NA), MacConkey Agar (MCA), and Salmonella–Shigella Agar (SSA). Serial dilution and pour-plate techniques were used to determine microbial load, while bacterial identification was carried out using colony morphology, Gram staining, and relevant biochemical tests. Results showed that microbial loads varied across sampling points, with downstream samples exhibiting the highest counts. Microbial loads on NA ranged from 2.4×10^5 to 4.6×10^5 CFU/mL, while MCA recorded 6.8×10^3 to 1.9×10^4 CFU/mL, and SSA ranged from 1.2×10^3 to 3.9×10^3 CFU/mL. A total of 24 bacterial isolates were identified, with *E. coli*, *Salmonella* sp., and *Staphylococcus* sp. each accounting for 16.67% of the isolates. *Streptococcus* sp., *Pseudomonas* sp., and *Klebsiella* sp. each constituted 12.5%, while *Shigella* sp. and *Bacillus* sp. represented 8.33% and 4.16%, respectively. Most isolates grew on Nutrient Agar, while selective media (MCA and SSA) confirmed the dominance of Gram-negative enteric bacteria. The presence of faecal indicators and pathogenic organisms suggests potential public health risks associated with the use of the stream for domestic, recreational, or agricultural purposes. Continuous monitoring and the implementation of appropriate water management strategies are recommended to safeguard community health.

NONLINEAR RANDOMISED COMPLETE BLOCK DESIGN AND ANALYSIS OF SAPONINS EFFECT ON CRUDE OIL SPILL REMEDIATION.

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ABSTRACT

In this study, an intrinsically nonlinear randomized complete block design (INRCBD) model with fixed and random block effects where the mean part of the INRCBD model follows a three-parameter Weibull growth function are formulated. The parameters of the formulated models are estimated using the estimated generalized least square (EGLS) approach where the variance components for random block and error terms are estimated via maximum likelihood estimator (MLE) and restricted maximum likelihood estimation (REML). The fitted models adequacy and goodness of fit are assessed using the median adequacy measures (MAM). The formulated models were applied to a $7^1 \times 6^1$ treatment combination data with 3 blocks for determining the effects of Saponins on oil spillage remediation. The results from MAM and IC revealed that the Weibull RCBD model with random block effect with parameters estimated using the EGLS-MLE is most adequate and provided the best fit compared to the other models. Also, the results further revealed that the EGLS-MLE estimator consistently outperformed EGLS-REML based on its parameter estimates lower standard errors. Hence, the estimates of the INRCBD model with random block effect from EGLS-MLE is more adequate, stable, and reliable.

BRIDGING QA GAPS WITH AI: A STUDY OF PREDICTIVE ACCURACY AND TEST AUTOMATION EFFICIENCY

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ABSTRACT

Modern software projects face immense pressure as release cycles shorten, and system complexity grows. Many studies show that more than 50% of defects are still detected after deployment, highlighting the limitations of traditional Quality Assurance (QA) methods. This paper presents a practical evaluation of how Artificial Intelligence can improve Software Quality Assurance by reducing manual effort and enabling earlier defect detection. Using data from two internal projects - containing an average of 420 historical defects, 1200 test cases and several weeks of system logs - the study assesses the impact of machine learning, natural language processing and anomaly-detection models. Results show that ML-based defect prediction achieved 72–84% accuracy, while NLP-driven test generation cut manual test design time by nearly 30%. AI-supported test maintenance further reduced script-update efforts by 35%, particularly during frequent UI changes. Real-time monitoring models were also able to detect unusual system behavior minutes before user-visible slowdowns. Although challenges remain, especially regarding data quality and model interpretability, the findings indicate that combining human expertise with targeted AI tools can significantly enhance QA efficiency and software reliability.

Keywords: Artificial Intelligence, Software Quality Assurance (SQA), Machine Learning, Defect Prediction, Automated Testing, Natural Language Processing (NLP), Predictive Analytics

VALORIZATION OF OLIVE MILL WASTE INTO ACTIVATED HYDROCHAR: ADVANCING CIRCULAR SOLUTIONS FOR WATER PURIFICATION

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ABSTRACT
In this study, activated carbon was synthesized from two-phase olive mill waste through a two-step process: hydrothermal carbonization, followed by chemical activation. The resulting AC showed a significant increase in carbon content from 44.43% to 89.64%, and a high specific surface area. The activated carbon was evaluated for the adsorption of Methylene Blue and Amitriptyline, demonstrating that the adsorption kinetics followed a Pseudo-Second-Order (PSO) model, while equilibrium data fit well with the Langmuir isotherm. The activated carbon exhibited impressive monolayer adsorption capacities mainly due to its large surface area. These results highlight the potential of valorizing olive mill waste for environmental applications. The study also underscores the effectiveness of HTC combined with activation in producing efficient biosorbents for persistent organic pollutants.
Keywords: Water treatment, Activated carbon, Hydrothermal carbonization, HTC, adsorption

AI-POWERED EARLY WARNING SYSTEMS FOR INFECTIOUS DISEASE OUTBREAKS: A MINI REVIEW

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ABSTRACT

The timely identification of infectious disease epidemics is necessary to prevent large scale outbreaks and minimize public health threats. In older surveillance it relies on clinical report and laboratory confirmation, thus may be delayed. The advances in AI and ML have the potential use as an early outbreak detection tool to analyze huge amount of data streams continuously. This mini review synthesizes prominent AI based strategies, particularly ML models, deep learning methods and NLP techniques. Machine learning approaches, including random forests, support vector machines and gradient boosting, use past case monitoring data as well as climate factors and population mobility to forecast the path of outbreaks. Deep learning approaches such as LSTM and Transformer based models are capable of capturing complex temporal patterns for the purpose of disease forecasting. NLP tools used for analyzing news reports, social media posts and official reports in order to identify early indicators of outbreaks, using LLMs to automatically triage and summarize. Existing platforms, like BlueDot, HealthMap, and GPHIN demonstrate the real-world use and promise of AI enabled surveillance. But there are obstacles, such as lack of data in resource poor countries and misinformation from online sources, privacy issues and the necessary provision for surveillance to be worked into public health systems. Future work focuses on multi source fusion, explainable AI and cost-effective solutions for global use. Early warning systems for infectious diseases, powered by artificial intelligence [AI], are paradigmatically transformative in that they enable faster and more accurate detection on a global scale, with unprecedented implications for epidemic preparedness and response.

Keywords: Artificial Intelligence, Early Warning Systems, Infectious Diseases, Machine Learning, Digital Epidemiology, Pandemic Prediction

PHYTOCHEMICAL SCREENING AND EVALUATION OF THE ANTIOXIDANT ACTIVITY OF THE HYDROETHANOLIC EXTRACT OF MOROCCAN *MYRTUS COMMUNIS L.*

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ABSTRACT

Myrtus communis L. (M. communis), commonly known as myrtle, is an aromatic shrub belonging to the Myrtaceae family, widespread throughout the Mediterranean basin. M. communis is a plant that has attracted considerable interest among scientists. It is recognized for its digestive, antiseptic, antimicrobial, astringent, and toning properties. Its bioactive compounds, including terpenes, phenolic acids, flavonoids, and anthocyanidins in various plant organs, contribute to its multiple pharmacological effects. The objective of this study is to determine the secondary metabolites of the hydroethanolic extract (MC-HEE) of M. communis, as well as to evaluate its antioxidant activity. M. communis leaves were used for the various tests. The antiradical activity of (MC-HEE) was evaluated using the ABTS (2,2'-azino-bis-(3-ethylbenzothiazoline-6-sulfonic acid)) reduction test. The results revealed the presence of flavonoids, phenols, tannins, coumarins, and saponins, with no flavone glycosides. Quantitative analysis showed a predominance of total polyphenols (4.061 ± 0.134 mg EAG/g extract) and flavonoids (3.918 ± 0.331 mg EQ/g extract). The extract showed significant antioxidant activity in trapping the ABTS free radical (PI = 70%). These results suggest that the hydroethanolic extract of myrtle has powerful antioxidant activity, which is mainly due to its phytochemical composition rich in secondary metabolites: polyphenols, flavonoids, tannins, and others.

Keywords: *Myrtus communis L.*, hydroethanolic extract and antioxidant activity.

A STUDY ON BACKGROUND NOISE REMOVAL USING DEEP LEARNING ALGORITHMS

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ABSTRACT

One of the vital research topic is noise removal in signal processing especially in the applications such as telecommunication,multimedia,speech recognition,restoration of music and speech enhancement.It degrades the quality of the audio significantly and the conventional approaches have its own limitations in handling complex and dynamic noisy environment.This paper explores the deep learning techniques for effective noise reduction in audio files and outline the methodology from data acquisition to evaluation of deep learning algorithms quantitative as well as qualitative methods.A custom dataset combines clean speech samples with various synthetic noisy data such as traffic, crowd chatter and machinery. This paper implements various deep learning algorithms for enhancing the speech and reducing the noise and produce the foundation for real time speech enhancement technologies.

STUDY OF THE PHYSICO-CHEMICAL AND BACTERIOLOGICAL QUALITY OF GROUNDWATER: CASE OF THE GHAZAOUET REGION (TLEMCEN PROVINCE)

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ABSTRACT
Water is a precious natural resource essential for multiple uses. When intended for food-related or hygiene purposes, it must meet high physico-chemical and microbiological quality standards. To assess the quality of water sources intended for human consumption in the Ghazaouet region, located in the far northwest of the Tlemcen Province, a physico-chemical and bacteriological analysis was carried out on several water samples collected from five water sources in the area (Ben Taghla, Ben Tawes, Ain El Mizab, Sidna Youchaa, and Ain Elkanout). Analyses were performed on these samples by measuring physico-chemical and bacteriological parameters such as temperature, pH, electrical conductivity (EC), turbidity, color, total hardness, suspended solids (SS), dry residue, carbonates (TA) and bicarbonates (TAC), nitrites (NO_2^-), orthophosphate, total coliforms, and fecal streptococci. According to our results, the physico-chemical analysis showed that the studied water sources comply with acceptable standards (Algerian standards and WHO guidelines). From a bacteriological point of view, two of the water sources were found to comply with the standards, while the remaining three exceeded the permitted limits. The high presence of microbial contaminants in the water may pose a significant health risk to residents who rely on these sources to meet their daily water needs.

Keywords: Water source, Quality, Physico-chemical, Bacteriological, Ghazaouet.

PROXIMATE ANALYSIS OF PEANUT PRODUCTS FROM COMPOSITE FLOUR OF WHEAT, GROUNDNUT, AND EGG FORMULATED FOR A MODERATE PERSON

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ABSTRACT

This study investigated the production and quality evaluation of peanut products formulated from composite flour consisting of wheat flour, groundnut, and egg. Three composite formulations were developed and assessed through proximate analysis and sensory evaluation using a 9-point hedonic scale. Proximate results showed that increasing the proportions of groundnut and egg enhanced the nutritional quality of the products, particularly in protein, fat, fibre, and ash content, while reducing carbohydrate levels. Sensory evaluation revealed no significant differences ($p > 0.05$) among samples for taste, aroma, colour, texture, flavour, and overall acceptability, although Sample A showed the highest overall preference. These findings demonstrated that composite flour technology can yield nutritionally enriched and consumer-acceptable peanut products. It is concluded that composite peanut formulations are feasible and nutritionally beneficial, and it is recommended that food producers adopt optimised composite blends for large-scale production and further product improvement.

Keywords: Composite formulation; Peanut product; Nutrient enrichment; Proximate analysis; Consumer acceptability

CHARACTERIZATION OF SALT-TOLERANT *BACILLUS SPP.* AS PLANT-GROWTH PROMOTING ENDOPHYTIC BACTERIA ENHANCING TOMATO SEEDLING GROWTH UNDER SALINITY STRESS

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ABSTRACT

Introduction: Plant growth-promoting endophytic bacteria (PGPEB) isolated from root nodules of forest trees in tropical and subtropical regions, enhance plant defense mechanisms against salinity stress. These endophytes hold great potential for improving cultivation practices in the saline-affected coastal farmlands of Bangladesh. Methods: Endophytic bacteria were isolated from the root nodules of one-year-old seedlings of *Samanea saman* and *Acacia auriculiformis*, and evaluated for their effects on tomato seedlings under 150 mM salt stress. Five bacterial isolates, identified as *Bacillus* spp. closely related to *B. pumilus, B. altitudinis, B. safensis,* and *B. xiamenensis* were characterized and confirmed by 16S rRNA. Results: These endophytes

exhibited diverse plant growth-promoting (PGP) traits in vitro, including biofilm formation, exopolysaccharide production, ammonia, HCN, IAA, GA, zinc solubilization, and nitrogen fixation. Among them, AARN-1 (*Bacillus altitudinis*) showed strong tolerance at 900 mM salinity. In soil and hydroponic trials, inoculation with these endophytes significantly enhanced tomato (*Solanum lycopersicum*) seedling growth under 150 mM salt stress, with AARN-1 demonstrating the greatest effect. AARNN-1 inoculated plants exhibited lower malondialdehyde and H_2O_2 levels, along with higher chlorophyll, proline, carotenoid, and stress-related enzyme production compared to uninoculated control. Conclusion: This study highlights *Bacillus* sp. as a promising candidate for eco-friendly biofertilizer development to improve crop cultivation in saline-prone regions of Bangladesh.

Keywords: Plant-growth promoting endophytic bacteria; Salinity; Soil; Hydroponics.

ASSESSING THE IMPACT OF AGRICULTURAL ACTIVITY ON THE BIODIVERSITY OF MOUNT CHENOUA IN TIPAZA REGION « NORTH OF ALGERIA »

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ABSTRACT

The ecosystem of the Mount Chenoua forest plays an important role in the Tipaza region of algeria, however it is threatened by agricultural activities. The impact of pesticides is a major concern due to their wide distribution and their harmful effects on biodiversity. The objective of this work is to carry out an assessment of the impact of agricultural practices in the study area. First by collecting data on agricultural practices through field surveys, in order to know the list of pesticides used, then by carrying out a bibliographic investigation on the impact on biodiversity (targeting and bioaccumulation, lifespan as well as the legal status of these pesticides). This study consisted of identifying and evaluating the effects of agriculture on the physical and biological environment of the ecosystem of this forest. Among the 10 farmers surveyed, 52 pesticides are used on 140 hectares. The production system is dominated by arboriculture. Agricultural practices destroy the different layers of the forest and negatively impact the flora and fauna of this ecosystem. The impact of agricultural activities on the forest ecosystem was assessed using a grid that balanced the sources of impact and the biophysical elements of the environment, ranging from moderate to major. To mitigate the negative impacts of agricultural activities on the forest ecosystem, the following practices should be encouraged, such as agroforestry, organic farming, agroecological farming, and conservation agriculture.

Keywords: Mount Chenoua, Biodiversity, Pesticides, Impact, Agriculture, Forest.

ELECTROCHEMICAL, STRUCTURAL AND THERMODYNAMIC INVESTIGATIONS OF CANNABIS SEEDS OIL (*CANNABIS SATIVA L*) AS A GREEN CORROSION INHIBITOR FOR C38 STEEL IN HCL

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ABSTRACT

The purpose of this study was to determine the effectiveness of a green and ecological formulation derived from cannabis seeds vegetable oil (*cannabis sativa L*) marked as CSO, obtained through hot pressing, as a corrosion inhibitor for protecting carbon steel (C38) from significant corrosion, notably in acidic environments such as HCl (1M). Experiments were carried out using the gravimetric weight loss (WL) of CSO was examined, and electrochemical methods at different concentrations: potentiodynamic polarization (PDP) and electrochemical impedance spectroscopy (EIS). The results from potentiodynamic polarization curves confirmed that CSO functions as an effective mixed corrosion inhibitor with predominant anodic activity. The inhibition efficiency of CSO increases with increasing concentration, reaching values of up to 91% at a concentration of 0.6 g/l. CSO forms a protective barrier layer on the surface of carbon steel, thereby reducing the contact area between the metal and the corrosive solution. The adsorption of CSO on the carbon steel followed Langmuir isotherm, the standard free Gibbs energy value is negative, which indicates the spontaneity of adsorption of the inhibitor on the metal surface. This value equal to -20 KJ.mol-1 between -20 Kj.mol-1 and -40 kJ·mol-1 shows that the green inhibitor is adsorbed by a mixed mechanism (physics-chemisorption).

Keywords: Cannabis seeds oil, Carbon steel, Corrosion inhibition, Electrochemical techniques, *Cannabis sativa L*.

CORROSION INHIBITION OF STEEL BY 2-ETHYL-6-NITRO-2H-INDAZOLE (6NE2): EXPERIMENTAL AND THEORETICAL INSIGHTS INTO ADSORPTION AND MECHANISTIC BEHAVIOR

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ABSTRACT

In this work, we investigate the corrosion-inhibition performance of 2-ethyl-6-nitro-2H-indazole (6NE2) on C38 steel in 1 M HCl using a combined experimental and theoretical strategy. Electrochemical measurements reveal the strong protective ability of 6NE2, with potentiodynamic polarization and EIS indicating inhibition efficiencies of 95.4% and 94.7% at 10^{-3} M. SEM imaging confirms the formation of a compact, homogeneous protective film on the steel surface in the presence of the inhibitor. Adsorption studies show that 6NE2 follows the Langmuir isotherm, and the thermodynamic parameters point to a spontaneous and stable adsorption process. Complementary DFT calculations and molecular dynamics simulations highlight favorable electronic interactions and stable adsorption configurations between 6NE2 and the steel interface. Together, these results demonstrate that 6NE2 acts through strong adsorption and efficient film formation, positioning it as a promising and environmentally benign corrosion inhibitor for steel in acidic environments.

Keywords: 2-ethyl-6-nitro-2H-indazole; Corrosion inhibition; Carbon steel; Electrochemical measurements; Theoretical calculations.

ECONOMIC ASSESSMENT OF NEEM ORGANIC FERTILIZER APPLICATION ON CUCUMBER (*Cucumis sativus* L.) PRODUCTION IN THE RAIN FOREST ECOLOGICAL ZONE

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ABSTRACT

Infertile soil results in lower quality cucumber fruits which are often rejected by consumers and thereby reducing farmers' income, making fertile soil a great requirement for profitability and yield maximization cucumber production. This study therefore analyzed the efficacy of Neem Organic Fertilizer (NOF) requirements for optimal yield and economic profitability for cucumber production. A field experiment was conducted in May 2025 at the Horticultural Technology Farm, Federal Polytechnic, Ilaro, Ogun State, (Latitude 6^0 53^1N and Longitude 2^0 58^1E). Nigeria. There were four organic rates of treatment comprising 0, 5, 10, and 15 t ha-1 of NOF brand. Treatments were arranged in a Randomized Complete Block Design (RCBD) with four replications. Fertilizers were applied at two weeks before planting. Data were collected on cucumber yield from six weeks after planting until the end of the experiment; the data collected were subjected to analysis of variance using GENSTAT discovery, and treatment means were separated using Duncan's Multiple Range Test (DMRT) at a 5% probability level**.** The economic assessment was carried out using the partial budget techniques involving the analysis of variable costs and benefits of the treatments involved in the experiment. Gross field benefit (GFB), Total cost (TC), Net benefit (NB) and Marginal rates of return (MRR) was calculated to determine the profitability. Neem Organic Fertilizer rates had a significant effect on fruit yield, cucumber plant nourished with 15t/ha application produced the highest fruit yield of 45.89t/ha but did not differed significantly from 39.66 and 37.39t/ha fruit yield produced from 5 and 10t applications. Conversely, treatments application of 5t/ha gave the highest MRR of ₦3,238 as it returned ₦2,238 at every ₦1,000 invested, while the lowest MRR was obtained from control that returned ₦1417 at every ₦1,000 invested. Economic analysis showed that 5 t/ha Neem Organic Fertilizer application is the most economical and more profitable than other rates of application and control.

Keywords: Cucumis sativus Neem Organic Fertilizer, Fuit Yield and Profitability

SUSTAINABLE OPTIMIZATION OF REVERSE OSMOSIS PRETREATMENT OF BRACKISH WATER USING COAGULATION-FLOCCULATION AND SLUDGE RECIRCULATION: A BOX-BEHNKEN APPROACH

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ABSTRACT

Optimizing pre-treatment in reverse osmosis (RO) demineralization systems is crucial for ensuring optimum water quality and prolonging membrane life by limiting rapid fouling. In this study, the treatment of water from the Aït Massoud dam, which supplies Maroc Central's reverse osmosis (RO) demineralization plant, was optimized using a Box-Behnken design. Three factors were studied: aluminum sulfate dose (10, 40 and 70 mg/L), polyelectrolyte dose (0.1, 0.2 and 0.3 mg/L) and recirculated sludge volume (5, 50 and 95 mL), to assess their impact on turbidity and oxidizable matter (OM) removal. The factors of recirculation sludge volume and aluminum sulfate dose affected the removal of turbidity and OM to the greatest extent possible. The optimum doses found for the removal of turbidity and OM were 46 mg/L aluminum sulfate, 0.22 mg/L polyelectrolyte, and 52 mL of sludge per liter of water. With these optimum doses, model results predicted 100% removal of turbidity and 72% removal of OM. These optimum doses were subsequently applied at full scale in the Maroc Central treatment plant. The findings indicated efficiency, for turbidity removal ranged from 94.12% to 98.49% and OM removal from 69.23% to 72.73%. The results were in close agreement with the model predicted values thus providing further assurance of the viability of this model for practical purposes under real operating conditions. Besides enhancing water treatment performance, the process resulted in a 38% reduction in sludge generation, 15% reduction in coagulant application, and 11.5% reduction in energy requirements while increasing membrane cleaning

cycles by 43%. Such improvements generated annual savings of about €60,150, strengthening the case for economic and environmental sustainability. However, the findings are site-specific and require validation under varying conditions and extended operation to assess long-term performance and reliability.

Keywords: Reverse osmosis; Box-Behnken design; coagulation flocculation; Sludge; optimization.

ECO-ENGINEERING OF OMFS: REDUCING ENVIRONMENTAL FOOTPRINT THROUGH ADVANCED FORMULATION AND RELEASE-CONTROL PROCESSES

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ABSTRACT

Fertilizers are essential for increasing crop yield, maintaining soil fertility, and ensuring nutrient supply. However, excessive use can lead to environmental issues such as nutrient loss and pollution. Eco-friendly organomineral fertilizers with slow and controlled release offer a sustainable alternative, enhancing nutrient use efficiency while reducing environmental impact. This study examines the formulation effects of organomineral fertilizers and sustainable biological coating material: pectin extracted from orange peels for its gelling, thickening, and stabilizing properties, as a barrier for controlled-release fertilizers (CRFs). By valorizing agro-industrial waste through aerobic and anaerobic biotransformation, nutrient-rich materials are converted into biofertilizers and combined with phosphogypsum (PG) to produce organomineral fertilizers with slow and controlled nutrient release. FTIR, SEM, pH analysis, NPK release, germination, and fertilization tests were conducted to assess the effectiveness of coated and uncoated fertilizers compared to conventional fertilizers. The best performing mixtures demonstrated optimal nutrient release profiles: M2-coated (compost) released only 22.05 (±1.43) % of nitrogen over 28 days, M5- coated (50% compost–50% PG) displayed a

sustained phosphorus release profile with 33.17(±2.16) % over 28 days, and M5-coated exhibited a controlled potassium release, reaching just 25 (±1.45) % within 28 days, meeting CRF standards for nutrient release over time. Results highlight the potential of these CRFs to enhance nutrient release efficiency, reduce leaching, and improve soil health, supporting climate-smart agriculture. This approach aligns with Conservation Agriculture principles and contributes to Sustainable Development Goals 2, 12, and 13 by promoting sustainable agriculture and minimizing environmental impact.

Keywords: Controlled-release systems, Pectin, Liquid digestate, Nutrient use efficiency (NUE), Phosphogypsum

ASSESSMENT OF THE IMPACT OF LITHOLOGICAL AND TOPOGRAPHICAL VARIABILITY ON SOIL MECHANICS AND ENVIRONMENTAL SUSTAINABILITY IN JORF LASFAR, FOCUSING ON THE DYNAMICS OF KARST AQUIFERS

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ABSTRACT
This investigation focuses on the geomechanical characterization of soils at the Jorf Lasfar construction site, located near the city of El Jadida in Morocco, in an environment characterized by natural rock formation procedures. The principal focus is to characterize the nature of the soils in order to select the most suitable construction techniques for the local conditions. The results show that the high-altitude areas are dominated by calcareous clay soils, characterized by specific plastic and mechanical behavior. Intermediate areas exhibit lithological diversity, including sandy-clay, marly-calcareous, and tuffaceous-calcareous formations, while low-lying areas are mainly composed of sandy soils with distinct geomechanical properties. This variability is a key factor in defining the construction methods appropriate for each sector of the site. To support this analysis, several tests were carried out, including direct shear tests to assess mechanical strength, water retention curves to assess hydraulic properties, and laboratory and in situ tests. These tests made it possible to establish correlations between the physical properties of the soils, their structure, and their mineralogical and lithological composition. This integrated approach facilitates a better understanding of soil behavior under environmental and mechanical constraints.
Keywords: Soil characterization, lithology impact, geomechanical properties, soil protection and reclamation, environmental monitoring

FACTORS AFFECTING CONSUMERS' PURCHASE INTENTION TOWARD GREEN PERSONAL CARE PRODUCTS

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ABSTRACT

Due to rising environmental concerns, sustainable consumption has become critical for individuals and businesses, with eco-conscious trends growing rapidly. Understanding consumers' attitudes toward green products and the factors affecting their purchase decisions is crucial. Personal care products are particularly meaningful in this context, as their frequent use and sensitivity to chemical content make them one of the categories that most clearly reflect consumers' environmental attitudes. This study aims to examine the factors that influence Turkish consumers' purchase intentions regarding green personal care products. In the first phase, a focus group study explored consumers' perceptions of green personal care products. Factors including environmental attitude, concern, quality, price, accessibility, and brand image were examined. Participants view "green" products positively, but ingredient concerns, high prices, limited variety, and brand distrust affect purchase intention. Despite strong environmental awareness and moral responsibility, some consumers have stated that they do not want to pay more for green products with similar performance. Economic considerations therefore play a decisive role in shaping actual purchasing behavior. Moreover, due to limited green variety, certain consumers prioritize continuity with familiar items but are willing to choose greener options—even at higher prices—when performance is equivalent. Reliable certifications build trust but participants noted that they could not fully define any brand as genuinely "green."Social media and peer recommendations influence decisions, but many consumers stated that they made their final decision based on their own research. And also product experience is highly valued, many participants prefer "refill " options for affordable trials. A quantitative study will follow the focus group to validate findings and test variable relationships. The research seeks to deepen insight into sustainable consumption and guide businesses in developing environmentally responsive strategies.

Keywords: Green Product , Purchase Intention , Green Marketing

This paper is derived from the unpublished master's thesis prepared by the first author at [Istanbul Technical University and Graduate School].

MİKROALG HASAT YÖNTEMLERİNİN ÇOK KRİTERLİ KARAR VERME MEKANİZMALARI İLE DEĞERLENDİRİLMESİ: TOPSIS ÖRNEĞİ

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ÖZET

Günümüzde sürdürülebilir enerji üretimi, çevresel yönetim stratejileri ve döngüsel ekonomi yaklaşımları kapsamında mikroalgler, yenilenebilir biyoteknolojik kaynaklar arasında giderek daha fazla önem kazanmaktadır. Mikroalgler; yüksek fotosentetik verimleri, hızlı büyüme özellikleri ve çeşitli çevresel ortamlara uyum sağlayabilme kapasiteleri sayesinde biyoyakıt üretimi, atık su arıtımı, gıda ve besin takviyeleri gibi pek çok alanda çevre dostu çözümler sunmaktadır. Bu çalışmada, mikroalglerin yaşam döngüsünün ekolojik performansı, çok kriterli karar verme yöntemlerinden biri olan TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) yöntemi kullanılarak kapsamlı bir biçimde değerlendirilmiştir. Yürütülen çalışma kapsamında, santrifüj, flokülasyon ve filtrasyon olmak üzere üç farklı hasat yöntemi; biyokütle verimliliği, enerji tüketimi, maliyet, su kullanımı ve çevresel etki kriterleri esas alınarak TOPSIS yöntemiyle karşılaştırmalı olarak değerlendirilmiştir. Yapılan hesaplamalar sonucunda flokülasyon yöntemi, genel performans açısından en uygun hasat alternatifi olarak belirlenmiştir. Çalışma kapsamında gerçekleştirilen duyarlılık analizi, kullanılan TOPSIS modelinin güvenilirliğini ve istikrarını doğrulamış, kriter ağırlıklarındaki değişimlere rağmen sonuç sıralamasında anlamlı bir farklılık gözlenmemiştir. Bu durum, modelin sağlam bir yapıya sahip olduğunu ve elde edilen bulguların literatürdeki benzer çalışmalarla yüksek düzeyde uyum gösterdiğini ortaya koymuştur. Elde edilen bulgular, mikroalglerin biyoteknolojik uygulamalarda etkin ve verimli biçimde kullanılabilmesi için doğru hasat yönteminin seçiminin büyük önem taşıdığını göstermektedir. Bu bağlamda araştırma, gelecekteki çalışmalar için hem teorik hem de uygulamalı düzeyde yol gösterici bir referans niteliği taşımaktadır.

Anahtar Kelimeler: TOPSIS, Mikroalgler, Hasat Yöntemleri, Biyokütle, Biyoteknoloji

EVALUATION OF MICROALGAE HARVESTING METHODS WITH MULTI-CRITERIA DECISION-MAKING MECHANISMS: A TOPSIS EXAMPLE

ABSTRACT

Today, within the scope of sustainable energy production, environmental management strategies, and circular economy approaches, microalgae are gaining increasing importance among renewable biotechnological resources.Microalgae provide environmentally friendly solutions in many fields such as biofuel production, wastewater treatment, food, and nutritional supplements thanks to their high photosynthetic efficiency, rapid growth characteristics, and ability to adapt to various environmental conditions. In this study, the ecological performance of the life cycle of microalgae was comprehensively evaluated using the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method, which is one of the multi-criteria decision-making techniques. Within the scope of the conducted study, three different harvesting methods—centrifugation, flocculation, and filtration—were comparatively assessed through the TOPSIS method based on the criteria of biomass productivity, energy consumption, cost, water usage, and environmental impact. As a result of the calculations, the flocculation method was determined to be the most suitable harvesting alternative in terms of overall performance. The sensitivity analysis conducted within the scope of the study confirmed the reliability and stability of the TOPSIS model used, and no significant difference was observed in the ranking of results despite changes in the criterion weights.This situation revealed that the model has a robust structure and that the obtained findings show a high level of consistency with similar studies in the literature. The results indicate that selecting the appropriate harvesting method is of great importance for the effective and efficient utilization of microalgae in biotechnological applications. In this context, the research serves as a guiding reference at both theoretical and practical levels for future studies.

Keywords: TOPSIS, Microalgae, Harvesting Methods, Biomass, Biotechnology

EVALUATION OF MAKSUTLU DAM LAKE (SİVAS, TÜRKİYE) WATER QUALITY IN TERMS OF ELEMENTAL LOAD

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ABSTRACT

This study aims to evaluate the suitability of irrigation water and the elemental composition of Maksutlu Dam Lake, located within Sivas Province and built for irrigation purposes. Water samples were collected from three stations in the dam lake during the dry (autumn) season, and elemental analyses were performed. Regarding irrigation suitability, the results of the sodium absorption rate (SAR), magnesium ratio (MgR), and percent sodium (% Na) indices indicated that the water is suitable for irrigation; however, the Kelly index (KI) suggested it is only marginally suitable. Concerning toxic elements, the HPI index (HPI > 100) showed that all stations were polluted. According to the MI index, all stations were classified as extremely polluted at level VI (MI ≥ 6). Based on the Surface Water Quality Management Regulation of Türkiye, the water quality classes were determined as follows: Class IV for lead (Pb); Class III for aluminum (Al); Class II for chromium (Cr), iron (Fe), nickel (Ni), zinc (Zn), copper (Cu), and arsenic (As); and Class I for manganese (Mn), cobalt (Co), selenium (Se), and cadmium (Cd).

Keywords: Dam lake, Pollution, Water quality, Irrigation water, Toxic element.

A STUDY ON THE ACTUARIAL CLIMATE INDEX FOR ISTANBUL

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ABSTRACT

This study aims to quantitatively assess the impacts of climate change by fitting the Actuarial Climate Index (ACI) for Istanbul using daily data covering the period 1981-2025. The ACI is an index developed to measure the effects of climate change and to serve as a decision-support tool across various sectors. The basic components of the ACI used in this study include high temperature (T90), low temperature (T10), extreme precipitation, wind speed, and drought. Although sea level is also a component of the ACI, its estimation was not included in this study due to insufficient data. The data were obtained from the NASA POWER LARC database, and the drought component was calculated using the consecutive dry days method. Daily data were aggregated to a monthly scale, and standardized anomalies were calculated for each component based on the 1981-2010 reference period mean and standard deviation. The results of the analysis indicate a pronounced increasing trend in both high and low temperature components in Istanbul after 1981. Seasonal fluctuations were observed in extreme precipitation and wind speed, whereas the drought component revealed negative anomalies, indicating prolonged dry periods. These findings demonstrate that Istanbul has been increasingly affected by climate change over the past four decades, with a noticeable rise in the frequency of extreme weather events. The results also support the need to re-evaluate risk assessments in sectors such as energy, agriculture and insurance. In the next stage of the study, the ACI components will be analyzed using machine learning (ML) techniques. The modeling of the temporal development of the ACI and making future projections aim to improve the forecasting of local climate risks and contribute to sustainable adaptation policies.

Keywords: Actuarial Climate Index, Climate Change, Extreme Weather, Machine Learning, Istanbul

METAL BORÜR KATALİZÖRLERİN SENTEZİ VE HİDROJEN ÜRETİM UYGULAMALARI

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ÖZET

Günümüzde fosil yakıtların yoğun kullanımı, mevcut rezervlerin hızla tükenmesine sebep olmaktadır. Bu kaynaklar aynı zamanda hava ve su kirliliği ile iklim değişikliği gibi çevresel sorunların başlıca nedenleri arasında yer almaktadır. Bu nedenle karbon içermeyen ve yanma sonucu yalnızca su açığa çıkaran hidrojen, sürdürülebilir enerji taşıyıcısı olarak öne çıkmaktadır. Ekonomik oluşu, depolama kolaylığı ve yenilenebilir bir enerji kaynağı olarak kullanılabilmesi, hidrojen enerjisini araştırmaların merkezine taşımaktadır. Kimyasal bileşikler ile hidrojen depolama ve geri kazanımı süreçleri sunduğu avantajlar ile dikkat çekmektedir. Sodyum bor hidrür ($NaBH_4$), yüksek teorik hidrojen depolama kapasitesi, düşük sıcaklıklarda hızlı hidrojen salımı ve stabil yapısıyla öne çıkan kimyasal hidrojen taşıyıcısıdır. Bu nedenle, $NaBH_4$'ün hidroliz reaksiyonunu verimli hâle getirecek yüksek performanslı katalizörlerin geliştirilmesi gerekmektedir. Katalizör olarak kullanılan metal nanopartiküller, reaksiyon kinetiklerini hızlandırarak hidrojen üretim verimliliğini artırmaktadır. Yaygın olarak kullanılan soy metallerin yerine bulunması daha kolay ve daha az maliyetli olan kobalt (Co) ve nikel (Ni) gibi geçiş metalleri tercih edilmektedir. Bu doğrultuda, geçiş metallerinin borür türevleri metal yüzeyinde daha fazla aktif merkez oluşmasına olanak tanıyarak katalitik aktiviteyi olumlu etkilemektedir. Bimetalik Co-Ni-B amorf nanopartiküller bu çalışmada kimyasal indirgeme yöntemi ile sentezlenmiştir. Sentezlenen Co–Ni–B nanopartiküller, azot atmosferi altında 250, 350 ve 450 °C sıcaklıklarda 2 saat ısıl işleme tabi tutulmuştur. Hidrojen üretim hızı, reaksiyon süresince açığa çıkan hidrojen gazının hacminin katalizör kütlesine ve zamana oranlanmasıyla hesaplanmıştır. Elde edilen sonuçlara göre, 250 °C'de ısıl işlem görmüş katalizör için hidrojen üretim hızı 1127 mL dk^{-1} $g_{kat.}^{-1}$, 350 °C için 1625 mL dk^{-1} $g_{kat.}^{-1}$ ve 450 °C için 930 mL dk^{-1} $g_{kat.}^{-1}$ olarak belirlenmiştir. En yüksek hidrojen üretim hızı 350 °C'de gerçekleştirilen ısıl işlem sonrası elde edilmiştir. Bu durum, optimum sıcaklıkta yapılan ısıl işlemin katalizör yüzeyinde daha homojen gözenek boyutu dağılımı, artan özgül yüzey alanı ve aktif yüzey merkezlerinin korunmasıyla ilişkilendirilmektedir. Bu yapısal özelliklerin, reaktanların katalizör yüzeyiyle etkileşimini kolaylaştırarak hidrojen üretim performansını artırdığı sonucuna varılmaktadır.

Anahtar Kelimeler: Hidrojen, katalizör, ısıl işlem, nanopartikül.

SYNTHESIS OF METAL BORIDE CATALYSTS AND THEIR HYDROGEN PRODUCTION APPLICATIONS

ABSTRACT

The common use of fossil fuels today has led to the rapid depletion of existing reserves. These resources are also among the primary reasons for environmental issues such as air and water pollution and climate change. Therefore, hydrogen stands out as a sustainable energy carrier because it is carbon-free and produces only water as a byproduct of combustion. Its cost-effectiveness, ease of storage, and potential use as a renewable energy source have placed hydrogen energy at the center of current research. Chemical hydrogen storage and recovery processes attract attention due to the advantages they offer. Sodium borohydride ($NaBH_4$) is a prominent chemical hydrogen carrier owing to its high theoretical hydrogen storage capacity, rapid hydrogen release at low temperatures, and structural stability. For this reason, it is essential to develop high-performance catalysts that can enhance the efficiency of the $NaBH_4$ hydrolysis reaction. Metal nanoparticles used as catalysts accelerate reaction kinetics and improve hydrogen production efficiency. Transition metals like cobalt (Co) and nickel (Ni), which are more abundant and less expensive, are preferred over noble metals, which are more common and expensive. In this context, boride derivatives of transition metals positively influence catalytic activity by enabling the formation of a higher number of active sites on the metal surface. In this study, bimetallic amorphous Co–Ni–B nanoparticles were synthesized via the chemical reduction method. The synthesized Co–Ni–B nanoparticles were subjected to heat treatment at 250, 350, and 450°C for 2 hours under a nitrogen atmosphere. The hydrogen generation rate was calculated by dividing the volume of hydrogen released during the reaction by the catalyst mass and reaction time. According to the results, the hydrogen generation rate was determined as 1127 mL min^{-1} $gcat.^{-1}$ for the catalyst heat-treated at 250°C, 1625 mL min^{-1} $gcat.^{-1}$ at 350°C, and 930 mL min^{-1} $gcat.^{-1}$ at 450°C. The highest hydrogen generation rate was achieved after heat treatment at 350°C. This outcome is attributed to the fact that heat treatment at the optimum temperature promotes a more homogeneous pore size distribution, increased specific surface area, and preservation of active surface sites. These structural features facilitate the interaction between reactants and the catalyst surface, ultimately enhancing hydrogen production performance.

Keywords: Hydrogen, catalyst, heat treatment, nanoparticle.

FABRICATION OF CO(LL)-FE(LL)-NI(LL)-BASED HETEROMETALLO SUPRAMOLECULAR POLYMER FOR ELECTROCHEMICAL SENSING OF 4-NITROPHENOL

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ABSTRACT

Creating a straightforward and accurate analytical technique to identify 4-nitrophenol (4-NP), one of the most hazardous organic pollutants that poses a constant threat to the environment, is essential. In this study, we designed a trimetallic-supramolecular polymer (HMSMP), combining three mostly abundant transition metals Co(II), Fe(II), Ni(II) salts and terpyridine moieties [4′,4′′′′-(1,4- Phenylene) bis(2,2′:6′,2′′-terpyridine)] (polyCoFeNi), to evaluate the sensitivity and selectivity of glassy carbon electrodes (GCE) toward 4-nitrophenol. Different characterization techniques were used to investigate the morphological and elemental compositions of polyCoFeNi. With a molecular weight of 2.43×10^6 Da of the polymer, a symmetrical ligand was formed with terpyridine moieties and trimetallic interactions. The electrochemical nature of polyCoFeNi_GCE was examined using CV analysis, revealing a low detection limit of 0.102 µM across a broad linear range of 1-2000 µM. A detailed reaction mechanism was postulated based on the kinetics study. Finally, stability, interference, reproducibility and applicability tests showed excellent recovery, anti-interference activity with high stability, affirming the sensor's novelity in practical reliability.

REAL -TIME HEARTBEAT, ECG, SpO_2 AND TEMPERATURE MONITORING USING A SMART IOT DEVICE

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ABSTRACT

Monitoring vital signs like ECG, heart rate, blood oxygen level (SpO2), and Temperature are essential to detect any abnormal health condition. existing monitoring systems are expensive and rely on hospital-grade equipment. This creates a clear need for an affordable, lightweight, and IoT-enabled device that allows continuous remote health monitoring for regular users, athletes, elderly persons, and patients. The main purpose of making this device is to make monitoring health more affordable and easily portable. This device can measure ECG waveform, heart rate, SpO_2, and body temperature in real time, display the waveform and data in the OLED display, send data to the cloud using WIFI, and user can check their vitals on their phone screen using Blynk IOT. This device is built with ESP8266 and the sensors used here, MAX30102 for heart rate and SpO_2, AD8232 for ECG waveform, and DS18B20 for temperature. This prototype measures and displays ECG waveform representing electric bits in the heart, Heart rate (BPM), Blood oxygen saturation (SpO_2), and Body temperature (°C) . This device transmits all vitals to the Blynk app. Lead-off detection helps users identify loose ECG electrodes. The heart rate and SpO2 are 98% accurate. This system provides an effective, low-cost solution to continuous health tracking, suitable for home use and portable. Especially more essential if there is an elderly person at home who requires continuous vitals tracking. For future implementation, we can use machine learning to analyze ECG patterns and predict arrhythmia, tachycardia, and bradycardia. We can also build a dedicated health dashboard to track daily/weekly trends of ECG, heart rate, temperature, and SpO_2. An alert system if the vitals fall. Overall, the project demonstrates that low-cost embedded hardware can be used to create an efficient and continuous health monitoring solution. It provides a foundation for future development into a more advanced clinical-grade diagnostic tool.

Keywords: ECG , SPo2 , IOT , Heart rate .

ADVANCES IN ECO-FRIENDLY ANTICORROSION COATINGS: RECYCLED POLYPROPYLENE AND ZNO NANOPARTICLES FOR ALUMINIUM ALLOYS-REVIEW

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ABSTRACT

Corrosion of aluminium alloys presents a major challenge in industrial and civil applications. Traditional protective methods, such as chromate- or epoxy-based coatings, pose environmental hazards due to their toxicity and limited recyclability. Zinc oxide (ZnO) nanoparticles are emerging as a sustainable material for corrosion protection because of their chemical stability, UV-blocking ability, and semiconducting nature. ZnO nanoparticles are produced by Aqueous Green Synthesis a Bottom-Up approach method. This review summarizes research progress on the incorporation of ZnO nanoparticles into polymer matrices, specifically polypropylene (PP). PP is valued for its recyclability, flexibility and hydrophobicity, while ZnO is known to enhance adhesion, mechanical strength, and corrosion resistance. Reported results highlight high performance, including corrosion efficiency up to 98%, polarization resistance values exceeding 90,000 omega cm^2, and contact angles above 140·degree for optimized ZnO-polymer coatings. This review discusses the mechanisms, performance evaluation, and fabrication methods of these coatings, emphasizing the potential of PP-ZnO nanoparticle as eco-friendly, high-performance protective layers for aluminium alloys.

Keywords: Aluminium alloys, Zinc oxide, Polypropylene, Nanoparticle, Anticorrosion, Eco-friendly coatings

USE OF AMORPHOUS AND APATITIC TRICALCIUM PHOSPHATE TO REMOVE Ni^{2+}, Co^{2+} AND Cu^{2+} FROM AQUEOUS SOLUTIONS

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ABSTRACT
Calcium phosphate materials have attracted significant attention in recent years owing to their wide range of applications. Their chemical resemblance to the mineral phase of calcified tissues, combined with their biocompatibility and biodegradability, makes them excellent candidates for bone and dental substitution. The ion-exchange properties resulting from the wide variety of anionic and cationic substitutions tolerated by their crystal structures have also been extensively exploited in analytical chemistry. Moreover, due to the coexistence of both acidic and basic surface sites, calcium phosphates have been studied as efficient catalysts for numerous chemical reactions. This work investigates the use of amorphous and apatitic tricalcium phosphate for purifying aqueous solutions initially containing metal ions. The experimental approach involves introducing either amorphous or apatitic tricalcium phosphate into separate aqueous solutions of Cu^{2+}, Co^{2+} and Ni^{2+} salts. After varying contact times, the phosphate solids are separated from the solutions and characterized using X-ray photoelectron spectroscopy (XPS), X-ray diffraction (XRD), and Fourier-transform infrared spectroscopy (FTIR). These analyses demonstrate the high capacity of both amorphous and apatitic phosphates to remove metal ions from solution. The elimination mechanism primarily involves ion exchange between calcium ions in the phosphate and metal ions in solution. In the case of nickel, this exchange occurs without significant alteration of the apatitic structure. In contrast, for cobalt and copper, the exchange process is accompanied by substantial structural modifications of the original phosphate phase.
Keywords: Amorphous calcium phosphate, Apatitic Calcium Phosphate, Dissolution-Precipitation, Exchange Ions.

TOWARDS A SUSTAINABLE AGRICULTURAL REVOLUTION WITH COGNITIVE SYSTEMS

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ABSTRACT

The world population grows tremendously and it is expected to touch 9 billion by 2037. It is predicted that the population will reach 10 billion in the year 2060. The rapid growth in the world-wide population makes the researchers to think about food production by considering the inefficiency of traditional systems due to climate change and the loss in biodiversity. The basic things of food, water, clothing and shelter are necessary to all human beings become a challenging task even though we are in technological era. The Government of India promotes the sustainable agriculture in various angles like improving the quality of crop seeds, crop rotation, usage of water in an effective way, soil management and soil health monitoring by raising the fund to proper utilization of resources such as drones and artificial intelligent based crop growth monitoring system with IoT. This work explains the various cognitive systems which involve machine learning, deep learning, artificial intelligence, IoT, data analytics, predictive analytics and so on. This work also highlights the challenges in the technology and ethics to reshape the agriculture into a sustainable and effective domain for providing food security in future.

Keywords: Artificial intelligence, Machine learning, Deep learning, Predictive analytics, food security and sustainable agriculture

CROSS VENTILATION IN DESERT HOMES: SPATIAL STRATEGIES FOR PASSIVE COOLING IN BISKRA.

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ABSTRACT

This paper deals with examining a passive cooling tool of cross ventilation in the housing of the south east Algerian desert city of Biskra which is an arid city with intense heat, low humidity and little wind circulation in it. Evaluation of the use of space and architecture in vernacular housing and modern housing determines how design of the building, direction, location of windows, courtyards, and spatial distributions influence air movement and thermal comfort. By using the mixed-method research strategy that involves environmental monitoring, computational fluid dynamics (CFD) model, and occupant survey, the study demonstrates that traditional residential buildings designed against the inward facing appearance, utilizing high thermal mass, favorable opening orientation have far better cross ventilation and comfortable indoor environment than modern housing that largely ignores passive design strategies. The results strongly state the vital importance of spatial awareness and culturally-grounded design interventions toward improving the interior air conditions and minimizing the use of mechanical air-conditioning systems. The study will make an input in the general idea of the discourse on climate-sensitive building in the hot-arid regions by providing scientifically-researched findings on how to incorporate advantageous cross ventilation in contemporary desert residences. Finally, it supports a new design paradigm that balances climate sensitivity, logic in space, and physical comfort of the occupants, as the environmental issues continue to increase.

Keywords: Cross Ventilation; Desert Architecture; Vernacular Housing; Spatial Configuration; Sustainable Residential Design.

SKYSCRAPERS OF SUSTENANCE: INTEGRATING VERTICAL FARMING INTO URBAN ARCHITECTURAL SYSTEMS.

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ABSTRACT

Vertical farming has increasingly become one of the most revolutionary foods to sustain the process of food production in urban cities as populations continue to flood the cities, and arable land in the countryside continues to diminish. A combination of vertical farming systems within the urban architectural context of the modern city will be explored in this research not just as an addition to the process of agricultural growth but as the essential part of designing future-proof buildings. In interdisciplinary research comprising of architectural analysis, models of environmental performance display and case study evaluation of such projects as Plantagon CityFarm, Sky Greens, and the Farmhouse Project, the study evaluates the spatial, energy, and resource optimization tactics of vertical agricultural buildings. The data point to the possibilities of hybrid architecture combining food production with living, working, and contributing to cities, which will allow cities to close the food miles, increase food security, and stimulate the flow of closed resources. Other aggravating issues addressed in the study are areas concerning regulatory framework, amount of energy used, and perception by the citizens and the researchers provide recommendations on the design and policy work in making the implementations scalable, context-sensitive. Finally, the study conceives the high-rise construction as a vehicle of ecological resilience and urban food sovereignty, strengthening the position of the building as a versatile ecosystem in times of climate change adaptation.

Keywords: Vertical Farming; Food-Energy-Water Nexus; Integrated Building Systems; Climate-Adaptive Architecture; High-Rise Agriculture.

SEASONAL ASSESSMENT OF PM2.5 IN CUMILLA DISTRICT, BANGLADESH USING MODIS-DERIVED GHAP DATA AND GOOGLE EARTH ENGINE

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ABSTRACT

Understanding seasonal air quality dynamics is essential for managing pollution in rapidly developing secondary cities. This study presents a seasonal analysis of fine particulate matter (PM2.5) in Cumilla District, Bangladesh, using the Global High-Resolution Aerosol Product (GHAP) processed within the Google Earth Engine (GEE) platform. The district boundary was simplified for efficient computation, and GHAP daily PM2.5 data were filtered and scaled to obtain physically meaningful concentrations. Seasonal composite maps—winter, pre-monsoon, monsoon, and post-monsoon—were generated through temporal averaging and clipped to the study area. Spatial distribution patterns and seasonal contrasts were visualized using standardized color schemes, while descriptive statistics for each season were derived through region-based reducers. The processed PM2.5 rasters and statistical outputs were exported for further geospatial interpretation in ArcGIS. The results reveal distinct seasonal variability and highlight localized pollution hotspots influenced by land use and meteorological conditions. This study provides the first satellite-driven, seasonally resolved PM2.5 assessment for Cumilla and demonstrates an efficient remote-sensing framework applicable to other data-limited regions for air-quality monitoring and policy support.

Keywords: PM2.5, Remote Sensing, Seasonal Variation, Google Earth Engine, GHAP, Cumilla District, Air Quality Mapping

GOLD NANOPARTICLES: PREPARATION, PROPERTIES, AND APPLICATIONS IN BIONANOTECHNOLOGY

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ABSTRACT

Gold nanoparticles (AuNPs) have emerged as a cornerstone in the field of bionanotechnology due to their unique physicochemical properties, biocompatibility, and ease of surface modification. These nanoscale materials can be synthesized through a variety of methods, including chemical reduction, biological synthesis, and physical techniques, each influencing particle size, shape, and stability. The tunable optical and electronic characteristics of AuNPs, such as surface plasmon resonance, enable their use in advanced biomedical applications including biosensing, drug delivery, imaging, and photothermal therapy. Furthermore, their ability to conjugate with biomolecules—proteins, DNA, and antibodies—enhances their specificity and functional versatility. The stability and inert nature of gold make these nanoparticles ideal for in vivo and in vitro systems, minimizing toxicity while maximizing performance. As research advances, AuNPs continue to revolutionize diagnostics, targeted therapeutics, and regenerative medicine. This integration of nanotechnology and biology marks a significant step toward precision medicine and the development of smart, multifunctional nanoplatforms for future biomedical innovations.

Keywords: Gold nanoparticles, synthesis, surface plasmon resonance, drug delivery, biosensing, bionanotechnology.

PLASTIC POLLUTION And BIODEGRADATION STRATEGIES

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ABSTRACT

Plastic pollution has emerged as a pervasive global environmental challenge, with over 300 million tons of plastic waste generated annually, much of which accumulates in landfills and oceans. Conventional plastics, primarily derived from petroleum, are resistant to natural degradation, leading to long-term persistence in ecosystems. This has dire consequences for marine life, terrestrial organisms, and human health due to microplastic contamination and associated toxic chemicals. Biodegradation, an eco-friendly approach involving the breakdown of plastics by microorganisms, presents a promising solution to this crisis. Various bacteria and fungi, including species of *Pseudomonas*, *Bacillus*, and *Aspergillus*, have demonstrated the ability to degrade polyethylene, polystyrene, and other plastics. Enzymatic degradation, especially through enzymes like laccases and PETases, has shown significant progress in breaking polymer chains into environmentally benign monomers. Recent advancements in genetic engineering and synthetic biology have further enhanced the efficiency of microbial degradation processes. Bioplastics, designed to degrade more readily, also contribute to sustainable waste management. However, biodegradation strategies require optimization to match the rate of plastic production. A multifaceted approach combining biotechnology, improved waste management, and global policy interventions is essential to mitigate plastic pollution and promote environmental sustainability.

Keywords : plastic pollution, biodegradation, micropastic, microbial degradation, genetic engineering.

CANCER CELL DETECTION USING MACHINE LEARNING: A COMPARATIVE STUDY OF KNN, SVM, AND RANDOM FOREST

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ABSTRACT

Accurately identifying cancerous cells at an early stage remains one of the most important challenges in medical diagnosis, as timely detection greatly improves treatment planning and patient outcomes. In recent years, machine learning has become a valuable tool for supporting clinicians by offering fast and consistent classification results. This study compares the performance of three commonly used algorithms—K-Nearest Neighbors (KNN), Support Vector Machine (SVM), and Random Forest (RF)—for cancer cell detection using the Breast Cancer Wisconsin Diagnostic dataset. Before training, the dataset was normalized, and relevant features were selected to minimize noise and enhance model performance. KNN was included as a simple reference model, though its results varied depending on feature scaling and the choice of k. SVM with the RBF kernel produced more stable decision boundaries and showed improved separation between benign and malignant cases. Among the three models, Random Forest achieved the strongest overall performance due to its ensemble nature and ability to handle complex feature interactions. The findings suggest that ensemble- and margin-based classifiers provide more reliable results for cancer detection than distance-based methods. Future studies may extend this work by testing deep learning models or combining multiple algorithms to further enhance diagnostic accuracy.

Index Terms: Cancer cell detection, machine learning, medical diagnosis, Support Vector Machine (SVM), Random Forest (RF), K-Nearest Neighbors (KNN), classification.

SYNERGISTIC ACTIVATION OF SOLAR PHOTOCATALYSIS AND OXIDANTS FOR RAPID DETOXIFICATION OF INDUSTRIAL EFFLUENTS

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ABSTRACT

This study investigates the solar-driven degradation of Acryl Brilliant Green (ABG), a carcinogenic and persistent dye commonly found in industrial wastewater, using advanced oxidation processes. Silver oxide (Ag_2O) microparticles (MPs) were synthesized via an eco-friendly and cost-effective green route and exhibited notable photocatalytic activity under natural sunlight, achieving approximately 83% dye degradation within 3 h. The introduction of peroxydisulfate (PS) as a co-oxidant significantly enhanced the photocatalytic performance, creating a strong synergistic effect that enabled complete ABG removal within just 21 minutes. This enhancement is attributed to the efficient activation of PS by Ag_2O under solar irradiation, generating highly reactive sulfate and hydroxyl radicals that accelerate the oxidative degradation pathway. Overall, the findings demonstrate that solar/Ag_2O/PS photocatalysis is a robust, sustainable, and energy-efficient approach for removing hazardous organic pollutants, offering valuable insights for the design of environmentally friendly water treatment technologies.

HARNESSING FRUIT AND NUT WASTE FOR THE EFFICIENT BIOSORPTION OF INDUSTRIAL DYE POLLUTANTS

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ABSTRACT

This study investigates the use of a mixture-based biosorbent, prepared from powdered corncob, almond, pomegranate, walnut, and peanut peels and shells, for the removal of triphenylmethane dyes from aqueous solutions. The biosorbent demonstrated high adsorption efficiency, cost-effectiveness, and environmental compatibility. Under optimized conditions; an adsorbent dosage of 0.3 g, an initial dye concentration of 300 ppm, and a contact time of 50 seconds; up to 98% dye removal was achieved, indicating rapid adsorption kinetics and substantial adsorption capacity. The adsorption process was influenced by solution pH, contact time, and dye concentration, suggesting that both electrostatic interactions and surface functional groups of the biosorbent contribute to dye binding. The study highlights that converting agro-industrial waste into functional biosorbents provides a sustainable, eco-friendly, and easily accessible approach for the treatment of industrial effluents. These findings offer practical insights for scaling up waste-based biosorption technologies for water purification and environmental remediation.

ASSESSING ANTHROPOGENIC IMPACTS ON THE KENITRA COASTAL DUNE CORDON (1999–2025): A REMOTE SENSING AND GIS STUDY

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ABSTRACT

In Kenitra Province, a notable dune-cordon system stretches about 70 km between Sidi Taibi and Moulay Bousselham. These dunes protect the fertile Gharb Plain from marine forces and support various socioeconomic activities. However, they face growing pressures from human activities. This study employs multi-temporal remote sensing and GIS analyses to quantify land-use dynamics across the dune cordon between 1999 and 2025.We processed Landsat 7 ETM+ (1999) and Sentinel 2 (2025) imagery, applying atmospheric correction, orthorectification, cropping, and reprojection, and conducted supervised Maximum Likelihood classification in ENVI. Through this approach, six thematic classes were delineated: open field agriculture, greenhouse agriculture, forest, natural vegetation, bare lands, and foredune-beaches. Training sites were selected using field surveys, very-high-resolution imagery, and ancillary data. Subsequently, the accuracy assessment of the land use maps showed overall accuracy rates of 91.06% for 2025 and 88.5% for 1999. The kappa coefficients were 0.89 for 1999 and 0.85 for 2025. Change detection analyses indicated a significant growth in agriculture, with cultivated land increasing from 753.5 ha in 1999 to 2,896.3 ha in 2025. This included a rise of 513 ha in greenhouse operations. Bare lands shrank from 4,163.8 ha to 1,635.5 ha. Forest cover also dropped by 964 ha. Such transformations can upset the dune system. They boost wind erosion and change sediment movement. Our findings point to the need for improved land-use planning and sustainable management. It is essential to balance agricultural expansion with the protection of dune ecosystem services. By identifying key transformation zones, this work sets the stage for focused conservation efforts and policy changes to protect the Kenitra coastal dunes.

Keywords: Coastal dunes, Land-use change, Erosion, Remote sensing, GIS.

FLOOR-LEVEL PREDICTION IN MULTI-STOREY MOSQUES USING INTERPRETABLE MACHINE LEARNING: A CASE STUDY FROM DHAKA, BANGLADESH

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ABSTRACT

Floor number is crucial for assessing the indoor climate in naturally ventilated multi-storey mosques. This is because it affects airflow, comfort levels, and environmental factors distributed throughout the building. Traditional evaluation methods generally ignore the effect of floor height. This is especially true in Dhaka, Bangladesh, where limited floor areas, overcrowding, and poor ventilation cause significant variations across floors in multi-story mosques. This study examines the impact of floor level on indoor conditions and identifies the key variables that contribute to differences across floors. A total of 415 data samples were collected through field surveys, including demographic parameters (age, gender, and clothing level) and environmental parameters (temperature, humidity, wind velocity, and lighting level). Three machine learning (ML) models, Decision Tree (DT), Random Forest (RF), and XGBoost, were used in the analysis. The performance of the models was assessed using the coefficient of determination (R^2), Mean Squared Error (MSE), and Root Mean Squared Error (RMSE). The importance of each feature was also evaluated using a permutation-based ranking method. All models achieved accuracies over 70%, and permutation analysis showed that temperature, humidity, and CO_2 were the most critical parameters affecting mosques. The results suggest that ML models can effectively explain the distribution of floor levels in multi-storey mosque environments. This study can help improve ventilation planning, manage crowd movement, and support the design of sustainable multi-storey mosques. Future research should use real-time sensors and gather data across different seasons and various types of mosques.

Keywords: Floor Level Prediction; Naturally Ventilated Mosques; Machine Learning (ML); Indoor Environmental Conditions

COMPARATIVE ANALYSIS OF FLOW THROUGH VARIOUS GAP-BLADE CONFIGURATIONS IN A LOW-SPECIFIC-SPEED CENTRIFUGAL PUMP

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ABSTRACT

Centrifugal pumps remain among the most widely used fluid-handling machines, and their operational efficiency is closely linked to global energy demand. In low-specific-speed pumps, hydraulic performance is particularly sensitive to internal flow structures, which are strongly influenced by impeller geometry. Previous experimental investigations have shown that incorporating gaps in impeller blades may improve energy characteristics in low-specific-speed designs. To further clarify the mechanisms responsible for these improvements, the present study focuses on the numerical analysis of internal flow behavior in several gap-blade impeller configurations. Computational fluid dynamics simulations were performed using a three-domain model comprising the suction pipe, impeller, and volute casing. Unstructured meshes with near-wall refinement were generated in Ansys Meshing 2023 R1, while steady-state flow fields were computed in Ansys CFX using the k–ω SST turbulence model. The analysis enabled the evaluation of hydraulic head, pressure distribution, velocity fields, and local flow instabilities under nominal (BEP) conditions. Four impeller variants were investigated: a reference impeller with continuous blades (*W0*) and three modified designs incorporating blade gaps at different locations (*W5* – gap toward the pressure side, *W6* – gap toward the suction side, and *W7* – double-gap configuration). The results reveal significant differences in internal flow patterns among the analyzed rotors. The reference impeller *W0* exhibits recirculation near the suction side and pronounced pressure gradients, contributing to increased hydraulic losses. In contrast, the *W5* configuration demonstrates improved streamline alignment, reduced separation, smaller low-pressure regions, and a smoother pressure rise, corresponding to enhanced energy transfer and higher predicted efficiency. The *W6* and *W7* variants show more irregular velocity fields and lower pressure uniformity, indicating greater susceptibility to flow instabilities and cavitation. Overall, the CFD analysis confirms that the position and configuration of the blade gap strongly affect internal flow structure and energy performance in low-specific-speed centrifugal pumps. The pressure-side gap (*W5*) provides the most favorable characteristics. Further experimental-numerical studies are recommended to support the optimization of future impeller designs.

Keywords: centrifugal pump, low specific speed, gap impeller, CFD

FOOT MOVEMENTS CLASSIFICATION BY MACHINE LEARNING ALGORITHM WITH OPTIMIZED ELECTROMYOGRAPHY FEATURES

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ABSTRACT

Electromyography (EMG) is a significant tool in biomedical engineering and medical diagnosis for evaluating muscle performance, identifying neuromuscular diseases, and guiding rehabilitation. However, the raw EMG signals, which are unfiltered and unprocessed, typically show random spike patterns. To increase signal quality, the study uses a Butterworth bandpass filter and Discrete Wavelet Transform (DWT) to reduce noise while keeping significant muscle activity patterns intact. Due to the high dimensionality and complex temporal patterns of EMG signals, feature extraction is crucial for significant classification. Common features are extracted, which include time-domain and frequency-domain features. Optimized feature selection is necessary for better classification results with two selected foot movements. The optimization of EMG features is conducted using Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), and Grey Wolf Optimizer (GWO). The optimized features are subsequently used by two classifiers: Support Vector Machine (SVM) and K-Nearest Neighbours (KNN). The classifiers' performance is evaluated in terms of accuracy and computational efficiency. Forty healthy subjects were instructed to perform two selected foot movements, dorsiflexion and plantarflexion, and EMG signals were recorded from the medial head of the gastrocnemius muscle. Experimental results demonstrate that the PSO optimizer performed the best among ACO, PSO, and GWO optimizers for feature selection. The model accuracy was evaluated using SVM and KNN. PSO achieved the highest accuracy of 95% with SVM, indicating its robustness in handling optimized EMG data. The results of the study contribute to designing an optimized EMG-based classification system to provide prosthetic limb control, especially for patients in Bangladesh, offering a more cost-effective solution to foot prosthesis treatment.

Keywords: EMG, Foot Movement, DWT, Feature Selection, PSO, ACO, GWO, SVM, KNN, Prosthetic Control.

ISOLATION OF SAHARAN ACTINOBACTERIA FOR BIOLOGICAL CONTROL AGAINST PHYTOPATHOGENS: TOWARDS SUSTAINABLE AGRICULTURE

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ABSTRACT

Throughout their lives, plants interact with various organisms, which can negatively or positively impact their health, leading to significant agricultural losses. Biological control, particularly through the use of antagonistic actinomycetes, represents a promising method to combat these phytopathogens. Therefore, this study aims to screen new strains of actinomycetes isolated from Saharan soil, which produce bioactive molecules that inhibit some phytopathogenic agents. For the isolation of Saharan actinomycetes, several soil samples were collected from various oases in Algeria. These samples were treated using the CaCO3 method and subjected to a series of decimal dilutions, and subsequently inoculated onto the CHV medium with or without selective agents, with incubation carried out at 30°C for 21 days. The antimicrobial activity of actinomycetes against these pathogens was assessed using the cross streaking method on ISP2 and YGB mediums. Incubation was done at 30°C for 24 hours for bacteria and up to 3 days for fungi (Aouiche et al 2013). This method of isolation among us has resulted in obtaining a significant number of actinomycete isolates with the potential to inhibit phytopathogenic bacteria and fungi, with the inhibition diameter reaching up to 40mm for some strains on the solid YGB medium. The intensity of the variable activity largely depends on the type or group to which the strains belong. These variations in the number of activities are due to the fact that a strain of actinobacteria can produce several antimicrobial molecules with different modes of action depending on the composition of the culture medium (Berdy, 2005 and 2012). In view of the results obtained, we can consider that our actinomycete isolates have the ability to inhibit certain phytopathogenic agents. The production, extraction, and characterization of these bioactive molecules is the subject of our current research.

Keywords: Actinomycetes, Bioactive molecules, Phytopathogenic agents, Biological control.

ENVIRONMENTAL AND CONSUMER HEALTH RISKS ASSOCIATED WITH MYCOTOXINS PRODUCED BY PHYTOPATHOGENIC FUNGI.

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ABSTRACT

Pathogenic fungi inflict great damage on plants, leading to their wilting, damage, or death in many cases, by secreting hydrolases that dissolve the cells of the plant tissue on which they feed. Among these plant-pathogenic fungi we find: *Botrytis ceneria*, *Fusarium oxysporum*, *Alternaria*, *Phytophthora infestans* ... these have a negative impact on health, food safety and lead to significant losses. Under certain climatic or storage conditions, these microorganisms can develop and lead to the production of mycotoxins, which can be harmful to the health of animals and humans, causing a number of disorders and even serious illnesses. These toxic metabolites therefore represent a major health problem. Around 25% of food products are contaminated with fungal toxins. The mycoflora is estimated to comprise between 200,000 and 300,000 species. There is therefore a wide diversity of mycotoxins. Of the more than 400 mycotoxins identified, only 30 or so have worrying toxic properties. Some of these toxins are thought to be carcinogenic or mutagenic, while others are toxic to the kidneys, nervous system or liver. It should also be noted that toxicity does not necessarily stem from the mycotoxin itself, but may be due to one of the metabolites produced by its degradation. Several species of micromycetes, mainly belonging to the four genera *Aspergillus*, *Penicillium*, *Fusarium and Alternaria*, are capable of excreting one or more mycotoxins: aflatoxins, ochratoxins, fumonisins, trichothecenes, patulin, zearalenone, alternariols…The lack of sanitary controls, poor food packaging (damp, hot, poorly ventilated storage areas) and the absence of strict regulations increase the risk of contamination by these metabolites. The frequency of contamination of foodstuffs available to the public and their mycotoxin content are becoming a serious threat to health.

Keywords: Mycotoxins**;** Phytopathogenic fungi **;**Food contamination**;** Toxicity**;** Food safety

EFFECT OF DIFFERENT LEVELS OF PHOSPHORUS AND BORON ON GROWTH AND YIELD OF TWO POTATO VARIETIES (Solanum tuberosum L.)

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ABSTRACT

The experiment was carried out to study the effect of different levels of phosphorus and boron on growth and yield of two potato varieties viz. 'Diamant' and 'Lal pakri' at experimental field of the Department of Crop Science and Technology, Rajshahi University, Rajshahi, during the period from November, 2018 to February, 2019. The experiment consisted of two factors; Factor A: Five levels of phosphorus and boron viz. F1 = 0 kg P and 0 kg B per ha,F2=50 kg P and 2 kg B per ha,F3=50 kg P and3 kg B per ha,F4=70 kg P and 2 kg B per ha, Fs=70 kg P and 3 kg B per ha and Factor B:Variety viz.V1 = 'Diamant' and V2 = 'Lal pakri'. The experiment was laid out with Randomized Complete Block Design (RCBD). Plant height (43.24 cm), number of leaves per plant (44.77), leaf length (30.20 cm), tuber length (11.33 cm), girth of tuber (19.33 cm), tuber weight per plant (292.90 g) were found maximum for Diamant variety combined with 70 kg P and 3 kg B per ha and the minimum results were found from Lal pakri variety combined with control treatment. The maximum number of tuber per plant (17.78) was recorded for Lal pakri variety combined with70 kg P and 3 kg B and the minimum result was found from Diamant variety combined with control treatment. In case of variety the highest yield (23.93 ton per ha) was obtained from Diamant variety and lowest yield (15.41 ton per ha) from Lal pakri variety. In case of different levels of phosphorus and boron the highest yield (22.32ton per ha) was found from 70 kg P and 3 kg B per ha and lowest yield (14.24 ton per ha) from control treatment. In case of treatment combinations among varieties with phosphorus and boron, Diamant variety combined with 70 kg P and 3 kg B per ha produced the highest yield (27.12 ton per ha) and the lowest yield (11.63 ton per ha) was obtained from Lal pakri variety combined with control treatment. In case of economic return, the highest cost of production, gross return, net return and benefit cost ratio (BCR) were recorded from Lal pakri variety with 70 kg P and 3 kg B per ha and the lowest was recorded from Diamant variety with control treatment. Considering the above findings, application of 70 kg P and 3 kg B per ha with Diamant variety appeared to be suitable for cultivation for high yield and the same levels of phosphorus and boron with Lal pakri variety for high economic return of potato.

GENOME-WIDE META-QTL ANALYSIS UNCOVERS STABLE LOCI UNDERLYING FRUIT TRAITS, PLANT MORPHOLOGY, ANTHOCYANIN REGULATION, AND BIOTIC STRESS RESISTANCE IN EGGPLANT

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ABSTRACT

Eggplant, a low-calorie vegetable rich in dietary fiber, essential vitamins, minerals, and polyphenolic compounds, has substantial nutritional and medicinal value. Meta-QTL analysis provides a powerful framework for identifying stable genomic regions that control quantitatively inherited traits by integrating QTL information from diverse studies conducted across different environments and genetic backgrounds. This research represents the first comprehensive meta-analysis in eggplant, targeting morphological, biochemical, fruit-quality, prickliness and biotic stress-related traits. The objective was to narrow down consensus genomic intervals and identify potential candidate genes relevant to these traits, thereby strengthening their application in breeding strategies. Using common markers in BioMercator

v4.2, published QTLs were put together based on LOD, PVE, and confidence interval (CI) criteria and then projected onto a consensus genetic map. Out of all collected QTLs, 391 (63.06%) were successfully projected onto a high-density consensus map, resulting in the identification of 84 meta-QTLs (MQTLs). The final MQTLs displayed an average CI of 7.1 cM, reflecting a 30.72% reduction from the initial average CI of 10.29 cM, thereby improving the precision of trait localization. Synteny and orthology analyses identified strong candidate genes within key MQTL regions. Functional annotations, including domain characterization, GO enrichment, and KEGG pathway analysis, highlighted conserved protein motifs and pathways related to regulation, metabolism, secondary metabolite production, and defense responses. Evidence from previous GWAS further validated the importance of several MQTLs. Overall, integrating markers tightly linked to these MQTLs can enhance genomic selection and strengthen marker-assisted breeding efforts in eggplant.

Keywords: Candidate gene, Genomic selection, Marker–trait association, Meta-QTL, Eggplant

REVERSIBLE DATA HIDING IN ENCRYPTED IMAGES

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ABSTRACT

Reversible Data Hiding in Encrypted Images (RDH-EI) plays a vital role in secure image management, particularly in cloud computing environments where data confidentiality and integrity are crucial. This project presents a high-capacity RDH-EI technique that embeds additional data into encrypted grayscale images while ensuring the original image can be perfectly recovered. The proposed method employs Edge-Directed Prediction (EDP) and Multi-MSB Self-Prediction, which together enhance embedding accuracy and capacity. EDP leverages edge information for precise pixelprediction, while Multi-MSB Self-Prediction refines embedding by utilizing multiple significant bits of pixels. The framework follows a three-step process: encryption of the original image, data embedding in the encrypted domain, and reversible data extraction with perfect image recovery. To further strengthen security, an OTP-based user authorization system is integrated, preventing unauthorized access and safeguarding sensitive data.The method achieves high embedding capacity, secure data protection, and lossless recovery, makingit suitable for applications such as medical imaging, cloud storage, and defense communication, where both data security and reversibility are essential.

Keywords: Reversible Data Hiding, Encrypted Images,Data security, Embedding Capacity, Image Recovery, Cloud Storage

MICROPARTICLES-ASSISTED ENGINEERING OF FUNGAL MORPHOLOGY FOR ENHANCED PRODUCTION OF HYDROLYTIC ENZYMES

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ABSTRACT

Filamentous fungi have been considered as factory for the production of valuable products in submerged fermentation. High growth rate and ability to utilize complex substrates make them superior than other microorganisms. However, their morphology in submerged fermentation is a big challenge in fermentation industry. Growth and morphology of a filamentous fungus, *Aspergillus oryzae* SBS50 was studied in submerged fermentation in the presence of microparticles. Addition of microparticles, viz. talc powder and aluminum oxide enhanced the production of various hydrolytic enzymes i.e. phytase, cellulase, xylanase and amylase significantly. The morphology of the fungus was also engineered by these microparticles during the production of hydrolytic enzymes. The size of fungal pellet was reduced up to 90% by the addition of microparticles. There was reduction in fermentation time from 96 h to 72 h. Reduction in fermentation time increased the productivity of the hydrolytic enzymes. Microparticles engineered the fungal morphology with concomitant increase in production and productivity of hydrolytic enzymes in submerged fermentation.

BIOLOGICAL CONTROL POTENTIAL OF GREEN LACEWINGS AND COMB-FOOTED SPIDER ON FALL ARMYWORM (*SPODOPTERA FRUGIPERDA*) AND SCREENING NATURAL ENEMIES OF FALL ARMYWORM BY USING MOLECULAR GUT CONTENT ANALYSIS

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ABSTRACT

The fall armyworm is an invasive and highly destructive agricultural pest which has the ability to invade a wide range of crops with polyphagous feeding behaviour. Biological control agents are employed to control fall armyworm in order to reduce reliance on chemical insecticides. Currently, several biological control agents are being used to manage fall armyworm, and among them generalist predators are getting more recognition as their broad range of predation ability. But predators-prey dynamic interactions and environmental DNA (eDNA) metagenomic analysis to detect prey preference in their diets research are underexplored. This research evaluated the predatory efficacy and intraguild effect two generalist predators on the fall armyworm with eDNA metagenomic analysis for natural enemies screening. In this study we used comb-footed spiders (Theridiidae sp.) and green lacewings larvae (*Mallada signatus*). Spiders and green lacewings larvae were tested individually and in combination with fall armyworm. We investigated predation efficacy and the intraguild predation effect on fall armyworm. The results revealed that both predators significantly reduced fall armyworm numbers individually or in combination. Predation capability of the predators is strongly influenced by prey size. Green lacewing larvae are most effective at preying on first and second instar and spiders entangled up to third instar larvae of fall armyworm. It was found that third instar larvae were not engulfed by green lacewing larvae but dead of third instar larvae cause to happen by biting of larvae of green lacewings. Intraguild predation was found between generalist predators that was not detrimental to fall armyworm control. Molecular gut content analysis of generalist predators revealed three fall armyworm species, viz. *Spodoptera frugiperda*, *Spodoptera litura*, and *Spodoptera exigua*. Molecular investigations confirmed that the generalist predator preys upon fall armyworms, and ecological experiments showed that the predators effectively consume them. The results of this study demonstrated that generalist predators might be able to lower falls throughout the early stages of development.

Keywords: Generalist Predators, Fall Armyworm, Predation efficacy, Intraguild predation, eDNA, Prey Preference

SICAK CIVATA DÖVME FRİKSİYONLU PRESLERDE BALATA İYİLEŞTİRME PROJESİ

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ÖZET

Cıvata üretiminde yoğun olarak kullanılan yöntemlerden birisi de sıcak şekillendirme tekniğidir. Bu üretim tekniğinde indüksiyon cihazlarında ısıtılan alaşımlı çelikler dövme presinde cıvata şekline gelmektedir. Sıcak şekillendirme tekniği ile cıvata üretiminde friksiyonlu presler yoğun olarak kullanılmaktadır. Friksiyonlu preslerin yoğun olarak kullanılması, presteki aksamların çabuk olarak aşınmasını sağlamaktadır. Bu parçalardan biri de preslerin balata sistemleridir. Bu proje, sıcak cıvata dövme hatlarında kullanılan friksiyonlu preslerin balata montaj sisteminin mekanik açıdan iyileştirilmesi sağlanmıştır. Eski sistemde balata, volanın bir tarafına sabitlenip diğer tarafından gerdirilerek takıldığından dolayı sürtünme kuvveti dengesiz dağılmakta, bu da düzensiz aşınmaya, enerji kayıplarına ve uzun bakım sürelerine yol açmaktaydı. Yapılan iyileştirme kapsamında, volan çevresine 20 adet cıvata eklenerek balata dış yüzeye eşit gerginlikte monte edilmiştir. Böylece, balatanın tüm yüzeyinde homojen sürtünme sağlanmış hem mekanik verimlilik hem de dayanıklılık artırılmıştır. Balata sistemindeki bu yeni ve inovatif tasarımla balata değişim süresi 8 saatten 2 saate düşmüş olup, balata ömrü %100 artmış, düzensiz aşınma tamamen ortadan kalkmıştır. Bu önemli gelişme ile birlikte pres duruş süreleri %75 azalmış, üretim sürekliliği ve proses güvenilirliği sağlanmıştır. Ayrıca enerji verimliliğinde belirgin iyileşme ve bakım maliyetlerinde kayda değer azalma elde edilmiştir. Sonuç olarak, proje hem operasyonel verimliliği hem de ekonomik sürdürülebilirliği güçlü biçimde desteklemiş; preslerin daha stabil, güvenilir ve enerji açısından verimli çalışmasını sağlamıştır.

Anahtar Kelimeler: pres, bağlantı elemanı, cıvata

LINING IMPROVEMENT PROJECT IN HOT BOLT FORGING FRACTION PRESSES

ABSTRACT

One of the most commonly used methods in bolt production is hot forming. In this production technique, alloy steels heated in induction devices are formed into bolts in a forging press. Friction presses are widely used in bolt production using hot forming. The extensive use of friction presses results in rapid wear of press components. One of these components is the press's pad systems. This project provides a mechanical improvement to the pad mounting system of friction presses used in hot bolt forging lines. In the old system, the pad was fixed to one side of the flywheel and tensioned from the other, resulting in uneven distribution of friction force, leading to uneven wear, energy losses, and extended maintenance times. As part of this improvement, 20 bolts were added around the flywheel and the pad was mounted to the outer surface with equal tension. This ensures uniform friction across the entire surface of the pad, increasing both mechanical efficiency and durability. With this new and innovative design in the brake pad system, brake pad replacement time has been reduced from 8 hours to 2 hours, brake pad life has been increased by 100%, and irregular wear has been completely eliminated. This significant improvement has reduced press downtime by 75%, ensuring production continuity and process reliability. Furthermore, significant improvements in energy efficiency and a significant reduction in maintenance costs have been achieved. As a result, the project has significantly boosted both operational efficiency and economic sustainability, ensuring more stable, reliable, and energy-efficient press operation.

Keywords: Press, Fastener, Bolt

COMPARATIVE ANTIOXIDANT PROFILING OF 18 PHARMA-GRADE COSMECEUTICAL OILS USING THE DPPH RADICAL-SCAVENGING ASSAY

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ABSTRACT

The antioxidant capacities of 18 pharma-grade cosmeceutical oils was evaluated using the DPPH radical-scavenging assay. The tested materials included fixed oils (moringa, avocado, black cumin, pomegranate, castor, macadamia, baobab, marula, jojoba, grape seed), essential oils (tea tree, peppermint, eucalyptus), phenolic-associated oils (bakuchiol, tamanu, black garlic), and squalene. Each oil was evaluated at concentrations of 0.5, 2.5, and 5 µg/mL, and antioxidant activity was determined using a 1 mM DPPH solution. Absorbance was recorded at 517 nm, and all measurements were performed in duplicate. Fixed oils demonstrated the strongest antioxidant capacity, with Moringa oleifera seed oil showing the highest inhibition (82.78% at 5 µg/mL), followed by avocado (55.73%), black cumin (41.56%), and pomegranate seed oil (42.78%). This study reports the first known DPPH antioxidant measurements for moringa (showed the highest antioxidant capacity) and baobab seed oils expanding current knowledge regarding their bioactive potential. Our findings highlight that lipid-compatible assays selectively favor lipophilic antioxidants, positioning fixed oils as superior candidates for incorporation into oil-based cosmeceuticals and provide a robust experimental foundation for future pharmaceutical investigations.

Keywords: DPPH assay, antioxidant activity, pharma-grade cosmeceutical oil, lipophilic antioxidants

OPTIMAL DESIGN OF FUZZY LOGIC CONTROLLER FOR AUTOMATIC VOLTAGE REGULATOR

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ABSTRACT

Optimal design of the fuzzy logic controller (FLC) for an automatic voltage regulator (AVR) is crucial due to its direct impact on power system stability, voltage quality, and generator performance. The AVR is responsible for maintaining the generator terminal voltage within acceptable limits despite load disturbances, nonlinearity, and environmental variations. While conventional PID-based AVR systems are widely used, they suffer from significant limitations, such as voltage overshoot, slow dynamic response, and sensitivity to parameter changes. This research presents the application of a Fuzzy Logic Controller (FLC)-based Automatic Voltage Regulator (AVR) system. The AVR is a device to control the reactive power and hold the terminal voltage of the synchronous generator at safer limits. In this paper, an FLC-based AVR system is analysed with triangular membership functions (MF). Two inputs, error voltage and change in error voltage, are considered as inputs of the FLC. In this study, triangular MF is considered, and the performance of the fuzzy AVR system with different proportional integral derivative (PID) controllers in the literature is checked. It is found that the proposed FLC-based AVR system reflects better performance in comparison to the PID controller-based AVR system. To overcome these problems, a Mamdani-type FLC employing triangular membership functions (MFs) is designed. Two inputs—voltage error and change in error—are utilised to generate a robust control action without the need for an accurate mathematical model. The performance of the proposed fuzzy-based AVR system is evaluated and compared with several optimised PID controllers. Keywords: Automatic Voltage Regulator (AVR), Fuzzy Logic Controller (FLC), PID Controller, Mamdani Inference, Power System Stabilisation, Voltage Regulation.

Keywords: Automatic Voltage Regulator (AVR), Fuzzy Logic Controller (FLC), PID Controller, Mamdani Inference, Power System Stabilization, Voltage Regulation.

PERFORMANCE EVALUATION OF PID VS. FUZZY LOGIC CONTROL FOR FIRST-ORDER WATER-LEVEL AND THERMAL SYSTEM

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ABSTRACT

Industrial control systems, such liquid-level and thermal heater operations, typically confront aggravating challenges such as overshooting their targets, delayed recovery times, and inconsistent results. These difficulties become most obvious when utilizing classic PID (proportional-integral-derivative) controllers, which must be carefully calibrated by hand and don't always cope well with changes or complex system behaviors. This research approaches those problems by comparing a standard PID controller to a Mamdani-type fuzzy logic controller, applying each to two simple process models constructed from basic concepts. Both controllers are implemented and tested in simulation: the PID is tuned using standard methods and adjusted for better performance, while the fuzzy logic controller for the heater uses triangular membership functions plus custom rules to limit overshoot and speed up stabilization. Through step changes and performance tests, the study finds that fuzzy logic can give smoother, more controlled transitions and cut down on overshoot in several scenarios, while PID controllers tend to react quickly but may cause more fluctuations at low setpoints. The results point to fuzzy logic as a sensible way to handle situations where PID falls short and suggest future work on combining or adapting these approaches for even better stability and flexibility in real operations.

Keywords— PID Control, Fuzzy Logic Control, Intelligent Control Systems, Hybrid Control Strategy, Water Level Regulation, Thermal Process Control, First-Order Dynamic Modeling.

RT35HC FAZ DEĞİŞTİREN MALZEMESİNİN BATARYA TERMAL SİSTEMİNDE ENTROPİ ÜRETİMİNE ETKİSİNİN SAYISAL OLARAK İNCELENMESİ

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ÖZET

Lityum iyon bataryalar günlük hayatımızda birçok farklı alanda çok yaygın olarak kullanılmaya başlanmıştır. Lityum iyon bataryalar günümüzde elektrikli ev aletlerinden, elektrikli iş aletlerine ve elektrikli araçlara kadar geniş bir yelpazede kullanılmaktadır. Bunun altında hiç şüphesiz lityum iyon bataryaların sunmuş olduğu yüksek enerji yoğunluğu, hızlı deşarj ve yüksek pil ömrü gibi avantajları yatmaktadır. Bu avantajlara rağmen lityum iyon bataryaların performansları sıcaklığa göre değişim göstermekte, düşük ve yüksek sıcaklıklarda verimleri önemli ölçüde düşmektedir. Lityum iyon bataryalar 15°C-40°C sıcaklık aralığında optimum çalışma sağlamaktadırlar. Diğer bir yandan lityum iyon bataryaların oluşturduğu batarya modülleri homojen sıcaklıkta olmalı ve modül içindeki sıcaklık farkı 5°C'yi aşmamalıdır. Lityum iyon bataryaları bu optimum çalışma sıcaklığı aralığında tutmak için kullanılan batarya termal yöntem sistemlerinin başında ise dışarıdan ilave bir enerji gereksinimi doğurmayan faz değiştiren malzemeler (FDM) gelmektedir. FDM'ler faz değişimleri esnasında gizli ısı çekerek sıcaklığı sabit tutmakta ya da sıcaklık artışını baskılayıcı etki oluşturmaktadır. Bu çalışmada batarya termal sistemlerinde yaygın olarak kullanılan RT35HC faz değiştiren malzemesi ile oluşturulan sistem ve doğal taşınımlı sistemin entropi üretimleri sayısal olarak hesaplanmış ve sonuçlar karşılaştırılarak batarya sisteminde FDM kullanılmasının entropi üretimine etkisi sayısal olarak incelenmiştir. Batarya deşarj hızı olarak 3C deşarj hızı, ortam sıcaklığı olarak 20°C ortam sıcaklığı, batarya tipi olarak 22650 tip silindirik lityum iyon batarya, 4 mm FDM kalınlığı ve 1 mm alüminyum hazne kalınlığı seçilmiştir. Sınır şartı olarak tabanın adyabatik, dış yüzeylerden ise ısı transfer katsayısı h=5 W/m^2K olacak şekilde taşınım olduğu kabul edilmiştir. Sonuçlar FDM kullanılması durumunda sisteme giren entropinin 5,64 J/K'den 6,27 J/K'e, sistemdeki entropi değişiminin 3,23 J/K'den 5,01 J/K'e çıktığını, batarya sıcaklığının 344,8 K'den 309,3 K'e, sistemden çıkan entropinin 2,66 J/K'den 1,38 J/K'e, entropi üretiminin ise %54 azalarak 0,25 J/K'den 0,11 J/K'e düştüğünü göstermiştir.

Anahtar Kelimeler: Batarya termal yönetimi, FDM, Entropi üretimi, Lityum iyon batarya

NUMERICAL INVESTIGATION OF THE EFFECT OF RT35HC PHASE-CHANGING MATERIAL ON ENTROPY PRODUCTION IN BATTERY THERMAL SYSTEMS

ABSTRACT

Lithium-ion batteries have become widely used in many different areas of our daily lives. Today, lithium-ion batteries are used in a wide range of applications, from electric household appliances to electric tools and electric vehicles. Undoubtedly, this is due to the advantages offered by lithium-ion batteries, such as high energy density, fast discharge, and long battery life. Despite these advantages, the performance of lithium-ion batteries varies with temperature, and their efficiency decreases significantly at low and high temperatures. Lithium-ion batteries provide optimal performance in the 15°C-40°C temperature range. On the other hand, the battery modules formed by lithium-ion batteries must be at a homogeneous temperature, and the temperature difference within the module must not exceed 5°C. Phase change materials (PCMs), which do not require additional external energy, are among the leading battery thermal management systems used to maintain lithium-ion batteries within this optimal operating temperature range. PCMs absorb latent heat during phase changes to maintain a constant temperature or suppress temperature increases. In this study, the entropy production of a system created using the RT35HC phase change material, which is commonly used in battery thermal systems, and a natural convection system were calculated numerically. The results were compared to numerically examine the effect of using PCM in battery systems on entropy production. The battery discharge rate was set to 3C, the ambient temperature to 20°C, the battery type to a 22650 cylindrical lithium-ion battery, the PCM thickness to 4 mm, and the aluminium tank thickness to 1 mm. As boundary conditions, the base was assumed to be adiabatic, and convection was assumed to occur from the outer surfaces with a heat transfer coefficient of h=5 W/m²K. The results show that when PCM is used, the entropy entering the system increases from 5.64 J/K to 6.27 J/K, the entropy change in the system increases from 3.23 J/K to 5.01 J/K, the battery temperature decreased from 344.8 K to 309.3 K, the entropy leaving the system decreased from 2.66 J/K to 1.38 J/K, and entropy production decreased by 54%, from 0.25 J/K to 0.11 J/K.

Keywords: Battery Thermal Management, PCM, Entropy Production, Lithium-ion Battery

PERFORMANCE EVALUATION AND TRADE-OFF ANALYSIS OF PAM, QAM, AND CPM IN HIGH-SPEED LIFI COMMUNICATION

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ABSTRACT

Light-Fidelity (LiFi) is a new technology that seems potential for high-speed wireless communication, providing enhanced data rates and secure transmission in optical wireless channels. This study presents a comprehensive performance evaluation and trade-off analysis of three widely used multi-level modulation schemes-Pulse Amplitude Modulation (PAM), Quadrature Amplitude Modulation (QAM), and Continuous Phase modulation (CPM)-in a high-speed LiFi system. In this work, several performance aspects of the LiFi link were examined, such as the achievable data rate, the usable communication distance, the signal-to-noise ratio (SNR), the bit error rate (BER), and the overall spectral efficiency. To evaluate the system, the experiments were carried out under practical indoor channel conditions. From the measurements, the LiFi setup was able to sustain data rates of up to 5 Gbps across a 10-meter path. The comparison among the modulation formats shows that QAM delivers the highest data throughput when the transmitter and receiver are placed at moderate distances, while CPM maintains lower BER when the link is extended. PAM behaves differently from the other two schemes. While it does not deliver the highest data rate or the lowest error level, it is easier to implement, and this makes it a practical option in situations where hardware simplicity is important. From the overall results, it becomes clear that the SNR, the link distance, and the achievable data rate are closely related, and changing one of them affects the others. The comparison also shows the limits of each modulation scheme in a real LiFi setup. These findings can help researchers and engineers decide which modulation approach is more suitable when designing or upgrading high-speed LiFi systems.

Keywords: LiFi, PAM, QAM, CPM, SNR, Data Rate, Transmission Distance, BER

ENDOPHYTES AND NANOPARTICLES COMBINATION

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ABSTRACT
A promising method for enhancing biological activity and fortifying plant defense mechanisms is the combination of endophytes with nanoparticles. Endophytes can serve as carriers that improve the stability and distribution of green nanoparticles within plant tissues as well as biofactories for their manufacture. Endophytes and nanoparticles exhibit synergistic benefits when combined, such as higher resistance to biotic stressors, improved plant growth promotion, and enhanced antimicrobial efficacy. By lowering chemical inputs and improving treatment efficacy, this integrated method also promotes sustainable agriculture and pharmaceutical uses. The synergistic mechanisms and new uses of the endophyte-nanoparticle combination are highlighted in this brief overview.
Keywords: Endophytes, Nanoparticles, Eco-friendly, Synergy, Antimicrobial, Sustainable.

GEOSPATIAL APPROACHES TO ENVIRONMENTAL MONITORING AND RISK ZONATION OF *MAHASTHAN* ARCHAEOLOGICAL HERITAGE SITE OF BANGLADESH

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ABSTRACT

Mahasthan, which is one of the most significant archaeological and cultural heritage sites in Bangladesh, is gradually becoming threatened by the developmental pressures of rapid urbanization, agricultural encroachment and environmental change. Although it is important, there has been little reliable and recent scientific research conducted under modern geospatial methods and techniques. In this study, a comprehensive archaeological monitoring and risk assessment framework is built through the combination of Geographic Information Systems (GIS), remote sensing, Digital Elevation Models (DEMs) and multi-temporal spectral indices (NDVI, NDBI, NDWI) to analyze the process of changes in land use and land cover (LULC) in the areas, topography and environmental changes compared between 1995 and 2025.The analysis demonstrates a significant decrease in the dense vegetation cover and permanent water bodies as well as a steady growth in the built-up areas with the resultant change in ecological balance. The analysis demonstrates a significant decrease in the dense vegetation cover and permanent water bodies as well as a steady growth in the built-up areas with the resultant change in ecological balance. High-risk sites, such as Mankalir Kunda Mound and Bairagi Bhita are predominantly associated with anthropogenic encroachment, vegetation loss and hydrological stress. The study provides evidence-based insights for heritage zoning, prioritizing conservation actions and implementing sustainable management strategies to safeguard *Mahasthan's* long-term preservation.

Keywords: Heritage, Archaeological Site, Environmental Monitoring, Geospatial, Risk Zoning.

A COMPARTMENTAL MATHEMATICAL MODEL FOR UNDERSTANDING HEART DISEASE DYNAMICS AND PREVENTION

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ABSTRACT

Heart disease persists as a significant contributor to global mortality rates, thus mandating the formulation of effective strategies centered on transmission, prevention, and control. This study investigates a compartmental mathematical model aimed at analyzing the dynamics related to heart disease transmission, integrating both lifestyle-associated and genetic risk factors. The model consists of six distinct compartments that signify various phases in the progression of the disease. We employ analytical techniques to validate the model's uniqueness and accuracy, ascertain the threshold at which the disease ceases to propagate, and compute the basic reproduction number utilizing the next-generation matrix approach. We demonstrate the global stability of the disease-free equilibrium through the application of Lyapunov fuction using Lasalle's invariance principle. Numerical simulations were performed to reinforce the analytical findings and illustrate the effectiveness of control measures intended to reduce the reproduction number. The findings underscore the critical importance of focusing on heart disease prevention and lifestyle modifications, thereby providing a comprehensive framework for the development of public health initiatives.

Keywords: Heart disease, lifestyle-associated, genetic risk factors, next-generation matrix, Lyapunov fuction.

SMART WEARABLES FOR HEALTH MONITORING USING NANOTECHNOLOGY

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ABSTRACT

Smart wearables have emerged as powerful tools in modern healthcare, offering continuous, non-invasive, and real-time monitoring of vital physiological parameters. The integration of nanotechnology has significantly enhanced the performance, sensitivity, and miniaturization of these devices. This paper highlights the design, development, and applications of nano-enabled wearable systems for advanced health monitoring. Nanomaterials such as graphene, carbon nanotubes, nano-silver, and polymer nanocomposites enable the creation of highly efficient and flexible sensors capable of detecting subtle biochemical and biophysical changes in the body. These nanosensors, embedded in smart patches, wristbands, textiles, and contact lenses, facilitate the monitoring of heart rate, blood pressure, glucose levels, body temperature, hydration, and respiratory activity. Nanotechnology improves the electrical conductivity, flexibility, biocompatibility, and durability of wearable sensors, making them suitable for long-term use and comfortable integration into daily activities. Recent innovations include nano-based sweat sensors, tear-fluid sensing contact lenses, and transdermal nanosensors capable of real-time molecular detection without invasive procedures. Such advancements support early diagnosis, personalized healthcare, and effective remote patient monitoring. The combination of nanotechnology with IoT, Bluetooth Low Energy (BLE), and artificial intelligence enables smart wearables to analyze and transmit health data instantly. These systems can identify abnormalities, provide alerts, and assist healthcare professionals in decision-making. Cloud-based platforms further enhance data management and telemedicine applications. However, challenges remain in terms of data privacy, long-term biocompatibility, sensor durability, and production costs. Continued research and standardization are essential to ensure the safe and widespread adoption of nano-enabled wearable technologies.

Keywords: Smart wearables, Nanotechnology, Health monitoring, Nano sensors, Smart textiles, Graphene, Carbon nanotubes, IoT healthcare, Remote monitoring, Personalized medicine.

MICROPLASTIC POLLUTION IN FRESHWATER ECOSYSTEMS

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ABSTRACT

Microplastic contamination has emerged as a pervasive threat to aquatic ecosystems globally, presenting significant risks to biodiversity, water quality, and human health. Microplastics, defined as plastic fragments smaller than 5 mm, originate from the breakdown of larger plastic debris and direct sources such as consumer products. Their resilience and minute size facilitate extensive dispersion through rivers, lakes, and oceans, where they are ingested by various aquatic organisms. The present study investigates microplastic concentrations across multiple freshwater sites and examines ecological impacts associated with chronic exposure. Field sampling was conducted in urban and rural water bodies, utilizing spectroscopic identification to characterize microplastics by polymer type. Results show higher concentrations in locations impacted by urbanization and industrial activity. Laboratory assays performed on fish and macroinvertebrate populations revealed microplastic accumulation in biological tissues, associated with decreased reproductive success and altered feeding behaviors. Furthermore, microplastics were found to adsorb persistent organic pollutants and heavy metals, compounding toxicological effects in aquatic food webs. The study underscores the urgent necessity for improved waste management strategies and stricter regulatory controls on plastic emissions. Effective interventions may include the development of biodegradable materials, enhanced public awareness campaigns, and targeted remediation of polluted sites. These findings have broad implications for conservation policy, highlighting the interconnectedness of environmental, social, and economic priorities. Addressing microplastic pollution will require interdisciplinary cooperation, ongoing monitoring, and adaptive management to safeguard freshwater ecosystems for future generations.

Keywords: microplastics, aquatic pollution, freshwater ecosystems, biodiversity, waste management, public health, spectroscopic analysis, ecological risk

INVESTIGATION OF STRUCTURAL AND OPTICAL CHARACTERISTICS OF UNDOPED AND NI-DOPED CuO THIN FILMS SYNTHESIZED VIA CBD

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ABSTRACT

This study aims to explore the influence of doping concentration (DC) on the structural and optical properties of pristine cupric oxide thin films (PCOTF) and Ni-doped cupric oxide thin films (NDCOTF). The PCOTF and NDCOTF were prepared onto glass substrates through the chemical bath deposition (CBD) technique with various DC of Ni. From FTIR spectra it is noticed that the absorption peaks at 608 and 444 cm^{-1} are assigned to CuO stretching vibrations, confirming the formation of PCOTF and NDCOTF. Ultraviolet–visible spectroscopy analysis revealed that absorbance (A) increased with Ni content but decreased with wavelength. Whereas, the transmittance (T%) of NDCOTF exhibited an inverse trend with respect to A. The highest T% of the PCOTF, approximately 70% in the visible region (VR), was found to be reduced with increasing DC. Furthermore, the refractive index enhanced with DC, attaining a maximum value of 2.64, while the skin depth diminished with higher DC. Meanwhile, the dielectric constant showed a slight increase with increasing DC. The optical band gap energy declined from 3.28 eV to 1.95 eV with increasing Ni content. In addition, reflectance, absorption coefficient, and extinction coefficient showed notable alteration with Ni-incorporation. From all this analysis, it can be predicted that the fabricated NDCOTF becomes suitable for applications in optoelectronic devices.

Keywords: Thin films, CBD, Ni-doped Cupric Oxide, Optical characteristics.

DECODING POLLUTANT TOXICITY USING CRISPR/CAS9 FOR APPLICATIONS IN MODERN ECOTOXICOLOGY

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ABSTRACT

Chemicals are widely used in agriculture to control pests and enhance productivity, yet their accumulation and long term presence in the environment pose significant risks to ecosystems and living organisms. With the rapid advancement of analytical technologies and high-throughput screening tools, toxicologists now have more precise methods to examine how these chemicals influence biological systems. Among the emerging tools, the CRISPR/Cas genome-editing system has gained considerable attention for its accuracy, efficiency, and relatively low cost. By enabling targeted modification of specific genes, CRISPR/Cas offers new opportunities to develop crops that are more resilient to chemical stressors and environmental pollutants, thereby helping protect yield losses caused by toxic exposures. In the field of ecotoxicology, CRISPR/Cas technologies are increasingly being applied to investigate how organisms respond to agricultural pollutants, antibiotic contamination, and other environmental threats. Through precise gene manipulation, researchers can identify and study key genetic pathways involved in toxicity responses, allowing a deeper understanding of how pollutants interact with biological systems. This approach not only supports the development of pollutant-resistant crop varieties but also contributes to the discovery of biomarkers and mechanisms relevant to environmental risk assessment. Furthermore, this review discusses the expanding potential of CRISPR/Cas within ecotoxicology, including its role in improving environmental monitoring, enhancing stress tolerance in plants, and reducing dependency on chemical inputs. While the technology offers many advantages, such as specificity and adaptability, it also presents limitations related to off target effects, regulatory concerns, and ecological safety. Overall, CRISPR/Cas represents a promising tool for advancing environmental research and developing sustainable solutions to pollution related challenges.

Keywords: CRISPR/Cas, Ecotoxicology, Chemical toxicity, Agricultural polution.

EVALUATION OF VISCOSITY OF 1,1,1,2-TETRAFLUOROETHANE (R134A) USING GREEN-KUBO APPROACH BY MOLECULAR DYNAMICS

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ABSTRACT

viscosity is estimated using the Green–Kubo formalism through time integration of the autocorrelation function of the off-diagonal components of the microscopic pressure tensor.Further refinement and comparison with experimental datasets are ongoing to improve model consistency. This work aims to establish a reliable molecular dynamics framework for predicting the viscosity of R134a, contributing to the development and evaluation of next-generation refrigerants and working fluids.The prediction of transport properties of refrigerants are essential for the design, optimization, and environmental evaluation of modern cooling and energy systems. Although experimental measurements provide valuable reference data, they are often limited by high costs, difficulties in accessing extreme thermodynamic conditions, and uncertainties at microscopic scales and difficult to find a good data set for simulation. In this context, Molecular Dynamics (MD) simulation serves as a powerful computational approach for exploring atomistic behavior and estimating transport properties with improved resolution. In the present study, Equilibrium Molecular Dynamics (EMD) simulations are being carried out to evaluate the viscosity of 1,1,1,2-tetrafluoroethane (R134a), a commonly used hydrofluorocarbon (HFC) refrigerant as a reference working fluid. The simulations are performed using the Large-scale Atomic/Molecular Massively Parallel Simulator (LAMMPS). An OPLS-based force field is being applied to model the R134a system, and the simulation outputs are being compared with available experimental data from the literature to assess the accuracy of the model. The system is equilibrated under NVT (constant number of particles, volume, temperature) and NVE (constant number of particles, volume, energy) ensembles, and the viscosity is estimated using the Green–Kubo formalism through time integration of the autocorrelation function of the off-diagonal components of the microscopic pressure tensor.

Further refinement and comparison with experimental datasets are ongoing to improve model consistency. This work aims to establish a reliable molecular dynamics framework for predicting the viscosity of R134a, contributing to the development and evaluation of next-generation refrigerants and working fluids.

Keywords: MolecularDynamics ; transport properties ;R134a; Green-Kubo; Viscosity;

ADVANCES IN CONCRETE 3D PRINTING FOR CIVIL ENGINEERING

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ABSTRACT

Civil engineering is developing rapidly as new technologies continue to shape the way structures are designed and built. One of the most exciting innovations is 3D concrete printing, which is gradually changing how construction is approached. This technology helps solve several challenges of traditional building methods, such as high labour costs, the time taken for formwork, material wastage, and safety issues on-site. It also plays an important role in reducing the environmental footprint by minimizing greenhouse gas emissions and optimizing material usage. With 3D printing, designers can create detailed and complex architectural forms that were once difficult or expensive to produce. Alongside this, digital tools like Building Information Modelling (BIM) are improving how projects are planned and managed, allowing for better coordination and accuracy. New cementitious materials and automated systems are also making printed structures stronger and more adaptable. In this review paper, the aim is to explore and analyse the existing literature available on 3D concrete printing. The focus is on understanding how this technology is used in modern construction, the ways to identify and manage printing defects, and the economic as well as environmental benefits that make 3D printing a promising method for future infrastructure development.

Keywords: 3D concrete printing, sustainable construction, Building Information Modelling (BIM), additive manufacturing, construction automation, innovative concrete materials.

MIXED MHD CONVECTION AND HEAT TRANSFER ENHANCEMENT IN A DRIVEN CUBIC CAVITY USING A CU–AL_2O_3/WATER HYBRID NANOFLUID

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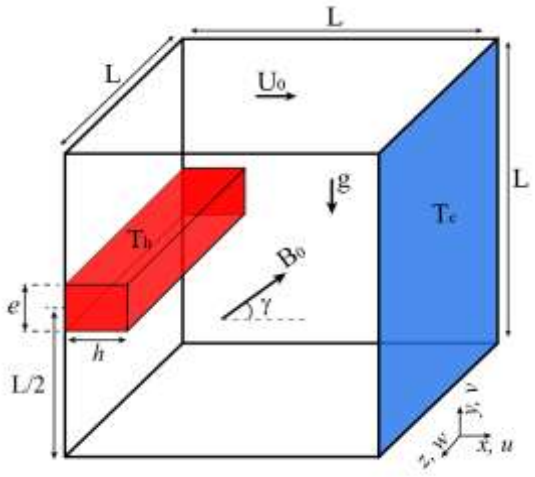
ABSTRACT
This work presents a numerical investigation of mixed magneto-hydrodynamic convection in a driven-wall cubic enclosure filled with a Cu–Al_2O_3/water hybrid nanofluid. An isothermal heating block at temperature T_h is attached to the left boundary, whereas the opposite wall is kept at a lower temperature T_c. A uniform magnetic field is imposed across the computational domain. The governing transport equations are resolved using the finite-volume approach combined with the SIMPLE scheme to ensure pressure–velocity coupling. The study examines the influence of key dimensionless parameters, namely the Richardson number (0.01–10), the Hartmann number (0–100), and the nanoparticle volume fraction (0-0.06). Flow structures and thermal fields are analyzed through streamlines, temperature contours, velocity distributions, and mean Nusselt numbers. Results show that higher Richardson numbers and particle concentrations improve heat transfer, whereas increasing the Hartmann number reduces the system's thermal efficiency.



A HYBRID CATBOOST-BASED SPATIOTEMPORAL FUSION MODEL FOR ACCURATE DAILY LAND SURFACE TEMPERATURE ESTIMATION ACROSS AFRICAN CLIMATE ZONES

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ABSTRACT
Accurate estimation of daily Land Surface Temperature (LST) at high spatial resolution is essential for environmental monitoring, precision agriculture, and climate assessment, particularly in regions with limited ground-based observations such as the African continent. This study proposes a hybrid spatiotemporal fusion framework based on the CatBoost model to integrate the high temporal frequency of MODIS data with the fine spatial resolution of Landsat imagery. In addition to LST observations, the model incorporates meaningful explanatory variables including surface albedo, surface radiation and selected spectral indices to enhance predictive performance. The framework was evaluated across different climate zones in Africa, achieving an R^2 of 0.89 and an RMSE of 3.41°C for daily LST estimation. The results demonstrate the robustness and transferability of the proposed approach over heterogeneous regions, highlighting its potential for large-scale applications in environmental monitoring, drought detection and precision irrigation.
Keywords: Land Surface Temperature; Spatiotemporal Fusion; CatBoost; MODIS; Landsat; Precision Agriculture;

ASSESSING GROUNDWATER DEPLETION IN BANGLADESH USING GRACE SATELLITE DATA: A HUMANITARIAN ENGINEERING APPROACH FOR SUSTAINABLE WATER MANAGEMENT IN DHAKA CITY

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ABSTRACT
Dhaka's rapid urbanization, extensive groundwater extraction, and declining natural recharge, groundwater depletion a major concern. Since no observation-well data were available, the primary sources of information used in this study were google earth engine (gee) and satellite-based datasets. The gldas model generated the land-surface components of soil moisture, canopy water, and surface water, which were further processed for the groundwater storage anomalies (gwsa) extraction, while the gravity recovery and climate experiment (grace) solutions supplied the monthly anomalies of terrestrial water storage (twsa) used in the study. Additionally, the hydroclimatic effects on groundwater dynamics were examined using rainfall, evapotranspiration, and temperature datasets from chirps, mod16, and era5.in the dataset created using the grace-gldas integration approach for the years 1994 to 2024, anomalies in groundwater storage were found across the whole year. Such data helps in tracking trends of progressive groundwater storage depletion over time as well as seasonal variations. The nature of the climate–groundwater interactions was revealed in the gee environment by time-series decomposition, trend analysis using linear regression, and correlation studies. The results showed that groundwater storage has been steadily decreasing, with the worst depletion happening in the months preceding the monsoon season, when water demand is at its peak. The geographical distribution of groundwater stress was depicted on the spatial trend maps, and it was most prevalent in dhaka's densely inhabited and heavily urbanized districts. This study shows a repeatable and data-independent method for tracking groundwater changes in areas with few field observations by using just cloud-based earth observation instruments. The results show the significance of satellite-based monitoring for sustainable groundwater governance in quickly expanding urban contexts and promote proactive water management measures.
Keywords*:* Groundwater depletion, GRACE data, sustainable water management, humanitarian engineering, Dhaka**;**

AN APPLICATION OF MIXED-INTEGER LINEAR PROGRAMMING TO MINIMIZE THE COST OF UNIVERSITY STUDENTS REQUIRED BASIC NUTRITIONAL REQUIREMENTS

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ABSTRACT

This study analyzes the effectiveness of linear programming (LP) methods in minimizing costs within budgets for student nutrition planning and small-scale agribusiness food formulation. In both cases, decision-making within limited resources while maintaining nutritional value is a challenge, where conventional empirical methods are not optimized. In the education-related field, a mathematical model is proposed for residential students, which helps meet nutritional needs at the lowest cost through daily food selection. According to the results, it is possible to implement a balanced diet plan for only 80 taka per day. In the agriculture-based field, since 70% of the production cost of small-scale farm food formulation is related to food, an optimization model is developed using local ingredients. It incorporates information on nutritional value, market prices, and industry practices. The model significantly reduces costs compared to conventional methods and provides insights into realistic decision-making through sensitivity analysis. The two models presented together show that LP-based optimization methods can play a significant role in cost-efficiency and effective use of resources.

Keywords: Nutrition planning; Linear programming (LP) methods; The agriculture-based field; Small-scale farm food formulation; LP-based optimization.

MODELING SHORT-RANGE ARTILLERY TRAJECTORIES WITH PROGRESSIVE DRAG AND WIND EFFECTS

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ABSTRACT

Accurate prediction of artillery trajectories has long depended on models that balance physical realism with computational simplicity. Traditional field methods relied on idealized equations or empirical firing tables, which often overlook the influence of aerodynamic drag and wind. The aim of this study is to reassess short-range projectile motion using modern physics while keeping the calculations accessible for manual or low-resource conditions. The work initiates three models of increasing fidelity on an ideal vacuum trajectory, a linear-drag formulation, and a full quadratic-drag model analyzed by a fourth-order Runge–Kutta scheme. Projectile specifications used in the simulations correspond to a 5 kg, 0.11 m diameter spherical iron shot with a drag coefficient of 0.47 and air density of 1.17 kg/m³ at 500 m altitude. Comparisons across models show how drag alters flight time, required muzzle velocity, and the presence of dual-angle firing solutions. For a 1,200 m target, the quadratic-drag model predicts feasible muzzle velocities ranging from roughly 143–156 m/s depending on angle, revealing substantial deviations from ideal estimates.The study also proposes a practical wind-correction method that uses an effective horizontal speed to adjust muzzle velocity under moderate headwind or tailwind conditions. This approach yields algebraic corrections that can be applied without computational tools and remains accurate within the tested range. The results indicate that simplified models are sufficient for conceptual understanding, but quadratic drag is necessary for realistic range prediction at typical artillery speeds. The main constraints arise from assuming constant drag coefficient, constant air density, no projectile spin, and equal launch-impact elevations. These restrictions limit applicability at long range, high altitude, or in transonic regimes, though the framework can be adapted for future refinement.

Keywords: Projectile Trajectories; Drag Coefficient Models; Linear Drag; Quadratic Drag; Runge–Kutta Integration; Wind Correction

INTERPRETABLE MACHINE LEARNING FRAMEWORK USING XGBOOST, CATBOOST, AND SHAP FOR PREDICTING YARN TENSILE STRENGTH

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ABSTRACT

Yarn tensile strength is a key quality indicator in textile manufacturing. It affects the performance, durability, and reliability of the final product. Traditional methods for testing yarn strength, such as laboratory tensile testing, are accurate but can be slow, costly, and not suitable for real-time monitoring in factories. This limitation creates the need for quick, accurate, and understandable predictive methods that can help improve processes and ensure quality. This study presents a machine learning framework to predict yarn tensile strength using ensemble models XGBoost and CatBoost. taking into account features such as fiber characteristics (length, fineness, and maturity), process parameters (spinning speed, twist, and tension), and environmental factors (temperature and humidity). To make the model's outputs clear and useful, it includes SHapley Additive exPlanations (SHAP), which provide scores for feature importance and show how each factor affects the predicted yarn strength. This helps engineers identify key factors that impact yarn quality and make informed adjustments in real time. Experimental results show that the proposed models achieve better prediction accuracy than traditional regression and simple neural network methods while remaining transparent in decision-making. Feature analysis with SHAP reveals that fiber fineness and twist level are the most significant factors affecting tensile performance, offering practical insights to optimize production. By combining prediction capabilities with understandability, this framework promotes efficient monitoring, reduces material waste, and encourages data-driven choices in textile manufacturing. In general, the study shows that interpretable machine learning models can connect high-accuracy prediction with practical insights, supporting smarter, more sustainable, and quality-centered textile production practices.

Keywords: Yarn Strength, Machine Learning, XGBoost, CatBoost, SHAP, Textile Engineering

NEUTRONIC MODELING OF A NUSCALE-TYPE SMR WITH OPENMC: ANALYSIS OF K_{EFF} AND BURNUP BEHAVIOR

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ABSTRACT
As the world transitions toward cleaner and more sustainable energy systems, Small Modular Reactors (SMRs) are emerging as a promising nuclear energy solution, offering enhanced safety, operational flexibility, and improved efficiency. This study presents a neutronic analysis of a NuScale-type SMR core using the Monte Carlo simulation code OpenMC. A detailed three-dimensional model of the reactor core has been developed to perform reference calculations, including the evaluation of the effective multiplication factor (k_{eff}) and neutron flux distribution under nominal operating conditions. Additionally, a preliminary fuel depletion (burnup) study is conducted using OpenMC's depletion module to assess the evolution of the reactor's neutronic behavior over time. These simulations aim to track changes in fuel composition and their impact on core performance throughout the irradiation cycle. The initial results will be compared with available benchmark data to evaluate the accuracy and reliability of the developed model. This comparison contributes to the validation of OpenMC for advanced reactor physics studies and reinforces its credibility for neutronic simulations of industrial-scale SMR concepts.
Keywords: OpenMC, Small Modular Reactor, NuScale, Monte Carlo Method, Neutronic Modeling, Burnup Analysis, Reactor Physics

ADSORPTIVE REMOVAL OF METHYLENE BLUE ONTO ACTIVATED CARBON PREPARED FROM BAMBOO: A STUDY OF KINETICS AND ISOTHERMS

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ABSTRACT

Activated carbon was successfully produced from bamboo, an abundant and low-cost lignocellulosic resource found in Morocco and across various African regions, via a physico-chemical activation process involving potassium hydroxide (KOH) and carbon dioxide (CO_2) at 850 °C for 2 hours. The synthesized adsorbent was tested for its capacity to remove methylene blue (MB) dye from aqueous media at 30 °C. Equilibrium adsorption behavior was best described by the Langmuir isotherm model, revealing a maximum monolayer adsorption capacity of 454.2 mg/g, indicative of uniform surface adsorption. Kinetic studies employing both pseudo-first-order and pseudo-second-order models showed that the latter provided a superior fit to the experimental data, implying that the dye uptake mechanism is primarily chemisorptive in nature. The kinetic constants were also calculated to gain deeper insight into the adsorption dynamics. Overall, the results underline the promise of bamboo-based activated carbon as a high-performance and sustainable material for the treatment of dye-laden wastewater.

Keywords: Activated carbon, Bamboo, Methylene blue, Adsorption isotherms, Adsorption kinetics, Dye removal

MULTIFUNCTIONAL Cu, B CO-DOPED ZnO PHOTOCATALYST: ORGANIC POLLUTANT DEGRADATION AND ANTIMICROBIAL COATINGS

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ABSTRACT

This study broadly discusses the synthesis, characterization, and application of Cu- and B-codoped ZnO photocatalysts for the photocatalytic degradation of organic pollutants and their antimicrobial and pathogen inactivation properties. This study employed the sol-gel method for the efficient synthesis of photocatalysts. The photocatalyst was evaluated against cationic dyes, most prominently malachite green, which gives more than 90% degradation efficiency under UV-Vis light irradiation. Which shows its strong photocatalytic potential. Prior to wastewater treatment, this material's antimicrobial property was also evaluated against Escherichia coli and Staphylococcus aureus. This investigation demonstrates strong pathogen deactivation effects against E. coli and S. aureus. The result of this investigation suggests its sustainability for antimicrobial coating. This diversified photocatalyst suggests a multifunctional and sustainable approach towards environmental remediation by both organic pollutant degradation and microbial control. Thus supporting environmental sustainability and green earth preservation. Cu and B-codoped ZnO's improved photocatalytic performance is attributed to the dopants' synergistic effects on charge separation and visible light absorption. This modification elevated the degradation efficiency of the organic pollutants found in the industrial wastewater as well as broadened the application under solar light irradiation. This modification makes it a cost-effective and sustainable solution. My future investigation will be focusing on improving the photocatalytic activity by varying the dopant composition and expanding microbial testing, including a wide range of pathogens. The aim of this project is to develop a multifunctional coating and water purification system in order to support the global efforts to protect water resources and promote environmental sustainability.

Keywords: Photocatalysts, pollutants, UV-Vis irradiation, pathogen, antimicrobial property, green environment.

STRESS TOLERANCE AND PLANT GROWTH PROMOTION THROUGH SEAWEED EXTRACT

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ABSTRACT
The implications of climate change are now clearly indicated by an increase in the frequency of cyclones, abnormal rainfall distribution, drought conditions, and increasing temperatures. Climate change has a significant influence on agricultural production, making it difficult to ensure food security as the population expands. Seaweed-based bio-stimulants have become a viable and efficient way to manage crop and soil stress and increase agricultural resilience against abiotic threats. Diverse bio-stimulatory effects of seaweed extracts are clearly evident, such as enhanced plant growth, nutrient uptake, and increased resistance to environmental challenges, including drought, salt, and abnormal temperature. It has been demonstrated that seed weeds have relatively low carbon footprints. Additionally, seaweed extracts enhance the plant-water relations, photosynthetic efficiency, stomatal function, and nutrient uptake. By strengthening the natural defence system of plants, seaweed extracts lessen the negative impacts of drought, such as decreased photosynthetic rates, cell membrane damage, osmotic imbalance, and increased oxidative stress. In this chapter, an attempt has been made to review the effect of seaweed and its biostimulatory properties on stress management in crop and soil health, especially abiotic stress management, highlighting advantages, limitations and potential developments.
Keyword: *Bio stimulant, Drought tolerance, Soil health, Stress management*

IDENTIFYING KEY INFLUENCERS OF PATIENT SATISFACTION USING AN EXPLAINABLE MACHINE LEARNING APPROACH

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ABSTRACT

Background: Patient satisfaction is a crucial measure of healthcare quality, influencing both health outcomes and care experiences. This study aims to identify the factors influencing patient satisfaction in healthcare facilities using machine learning algorithms due to their strong predictive capabilities. Methods: A cross-sectional survey was conducted with 312 patients from two private hospitals in Rangpur, Bangladesh. Machine learning models, including LightGBM, Random Forest, XGBoost, and CatBoost, were used to predict patient satisfaction, and SHAP value analysis was employed for interpretation. Results: The LightGBM classifier (before SMOTE) outperforms other models across metrics, with the highest accuracy, MCC, and ROC-AUC scores, establishing it as the optimal predictive model for this study. SHAP analysis further reveals that factors such as treatment plan, age, appointment ease, waiting time, and medication details significantly influence satisfaction levels. Overall, results indicate that structured interactions, shorter waiting times, and clear communication are associated with higher satisfaction, while extended waiting times and lack of decision involvement negatively impact patient experiences. Conclusion: To enhance patient satisfaction, healthcare providers should prioritize improving communication, reducing wait times, and offering clear treatment plans. Future research should explore additional factors to refine predictive models. The LightGBM classifier provides valuable insights into the key determinants of patient satisfaction, enabling healthcare practitioners and researchers to utilize it for targeted prediction and analysis in their specific contexts.

Keywords: Patient satisfaction, machine learning, Bangladesh, LightGBM, SHAP

THE CONVERGENCE OF BIOINFORMATICS AND OMICS TECHNOLOGIES IN BIOMEDICAL DISCOVERY

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ABSTRACT

Large-scale, integrated analysis of intricate molecular systems has been made possible by bioinformatics and omics technologies, which have transformed biological research. High-throughput omics techniques, such as transcriptomics, proteomics, metabolomics, and genomics, when combined with sophisticated bioinformatics tools, enable thorough investigation of biological processes at several levels. This integration advances functional genomics and precision medicine by accelerating the identification of regulatory pathways, gene-disease associations, and disease biomarkers. Researchers can use computer algorithms, machine learning models, and predictive analytics to extract important biological insights from massive datasets generated by omics platforms. Furthermore, the interpretation of intricate relationships between genes, proteins, and metabolites is supported by cutting-edge techniques for data visualization and network analysis. Although there has been significant development, there are still issues with data standards, interoperability, and the integration of multi-omics data to improve biological validity and clinical relevance. These issues are being addressed by ongoing advancements in artificial intelligence, cloud computing, and big data frameworks, opening the door for systemic biology modeling and tailored treatment approaches. In the end, the fusion of omics and bioinformatics continues to advance biomedical science by providing a better comprehension of health, disease causes, and possible treatment approaches.

Keywords: bioinformatics, omics, multi-omics integration.

RESEARCH ON STRUCTURING OF SEALING SURFACES

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ABSTRACT
Gaskets are a group of design solutions used to seal the surfaces of components that remain stationary relative to each other. The tightness level of a given fitting element, such as a flange-bolted joint, depends on the quality of the sealing and mating surfaces (determined by parameters such as microstructure, waviness, or hardness). This paper proposes a novel approach to shaping the sealing surface microstructure, aimed at inducing flow effects that lead to increased flow resistance of the sealed medium and improved tightness. The tightness characteristics were experimentally determined for two gasket variants: a structured gasket and a quasi-smooth gasket, which was adopted as the reference. Experimental results indicated that structured gaskets achieve a significantly lower leakage rate compared to quasi-smooth gaskets. This increase in tightness is particularly evident at relatively low values of the compressive force applied to the gasket. To identify the flow phenomena occurring at the interface between the sealing and mating surfaces, a preliminary, simplified numerical CFD model was developed. The study demonstrated the potential to improve tightness by inducing a fluid flow circulation effect. Finally, directions for further research on the presented concept are outlined, with particular emphasis on the limitations and challenges associated with the development of the numerical CFD model.
Keywords: flange-bolted joint; gasket; tightness improvement; CFD

TERMAL YORULMA ÇATLAKLARININ KAYNAK PROSEDÜRÜ İYİLEŞTİRMELERİ İLE ÖNLENMESİ VE KALIP ÖMRÜNÜN ARTIRILMASI

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ABSTRACT
Alçak basınçlı döküm (LPDC) prosesinde kullanılan kalıp bileşenleri, ürün geometrisinin doğruluğunu, yüzey kalitesini ve üretim kararlılığını doğrudan etkileyen kritik elemanlardır. Kalıplar üretim sırasında yüksek sıcaklıktaki sıvı alüminyumla tekrarlı şekilde temas ettiğinden yoğun termal yük altında çalışır ve bu durum tasarım değişiklikleri, tadilatlar ve bakım uygulamalarının doğru yönetilmesini gerekli kılar. Bu bağlamda kaynak işlemleri, kalıp ömrünü uzatan ancak doğru uygulanmadığında hasara neden olabilen önemli bir bakım adımıdır. Kalıplarda sıklıkla gözlenen hasarlardan biri termal yorulmadır. Literatürde termal yorulma; sıcaklık değişimleri, yüzeydeki sıcaklık gradyanları ve kısıtlı termal şekil değiştirmeler altında oluşan tekrarlı termal gerilmeler sonucu makroskobik çatlakların meydana geldiği bir yorulma türü olarak tanımlanmaktadır. Bu çatlaklar özellikle keskin geçişler, maça birleşimleri ve ısı yoğunlaşmasının arttığı bölgelerde hızla ilerleyerek kalıp performansını olumsuz etkiler. Bu çalışma, yeni üretilmiş bir kalıpta tasarım değişikliği sonrası alt maça bölgesinde gerçekleşen kaynak uygulaması sırasında ortaya çıkan termal yorulma çatlağını ele almaktadır. Çatlağın konumu nedeniyle standart kaynak prosedürleri yetersiz kalmış ve bu bölgeye özel optimize edilmiş bir prosedür geliştirilmiştir. Uygulamada kontrollü ön ısıtma, uygun dolgu malzemesi seçimi ve gerilim giderme ısıl işlemi birlikte kullanılmıştır. Kaynak sonrası kalıp işlenerek üretime alınmış ve seri üretim boyunca düzenli olarak izlenmiştir. Yapılan kontroller, çatlak ilerlemesinin durduğunu ve yapısal bir bozulma oluşmadığını göstermiştir. Sonuçlar, optimize edilmiş kaynak prosedürünün kalıp dayanımını artırdığını, bakım sıklığını azalttığını ve tadilat maliyetleri üzerinde olumlu etkiler sağladığını göstermektedir.

Anahtar Kelimeler: Döküm Kalıpları, Kaynaklı İmalat, Alçak Basınçlı Döküm

PREVENTION OF THERMAL FATIGUE CRACKS AND EXTENDING MOLD LIFETIME THROUGH IMPROVED WELDING PROCEDURES

ABSTRACT

Components of molds used in the low-pressure die casting (LPDC) process are critical elements that directly influence dimensional accuracy, surface quality, and production stability. Since molds repeatedly come into contact with high-temperature molten aluminum during production, they operate under severe thermal loads, making proper management of design changes, repairs, and maintenance practices essential. In this context, welding operations represent a significant maintenance step that can extend mold life but may also cause damage if not applied correctly. One of the most frequently observed failures in molds is thermal fatigue. In the literature, thermal fatigue is defined as a fatigue mechanism in which macroscopic cracks occur due to cyclic thermal stresses arising from temperature fluctuations, surface temperature gradients, and constrained thermal deformation. These cracks particularly propagate rapidly in areas such as sharp transitions, core joints, and regions with increased heat concentration, ultimately reducing mold performance. This study addresses a thermal fatigue crack that emerged in the lower core region of a newly manufactured mold following a design modification and subsequent welding operation. Due to the crack's location, standard welding procedures were insufficient, and a customized, optimized procedure was developed specifically for this area. The procedure employed controlled preheating, appropriate filler material selection, and stress-relief heat treatment in combination. After welding, the mold was machined and introduced into production, where it was monitored regularly throughout serial manufacturing. Inspections revealed that crack propagation had stopped and no structural deterioration occurred. The results demonstrate that the optimized welding procedure enhanced mold durability, reduced maintenance frequency, and positively influenced repair costs.

Keywords: Casting Molds, Welded Repair, Low-Pressure Die Casting

CNC TEZGÂHLARINDA POST-PROCESSOR İYİLEŞTİRMELERİ VE PROB ENTEGRASYONU İLE ÜRETİM VERİMLİLİĞİNİN ARTIRILMASI

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ABSTRACT

Geçmişte ahşap malzemeden üretilen jantlardan, günümüzde alüminyum alaşımlı veya kompozit yapılı jantlara doğru bir evrim süreci yaşanmıştır. Bu süreçte birçok üretim yöntemi geliştirilmiş ve uygulanmış olup, bu yöntemler üzerine çalışmalar hâlen devam etmektedir. Günümüzde ise otomotivlerde kullanılan jantların büyük çoğunluğu alüminyum alaşımlı olup, alçak basınçlı döküm yöntemiyle üretilmektedir. Dökümde kullanılan kalıpların işlenmesi ve genel talaşlı imalat yöntemleriyle ilgili birçok akademik ve sektörel çalışma mevcuttur. Bu çalışmada, CNC tezgâhlarda kullanılan post processor yazılımlarına entegre edilen yeni nesil iyileştirme çalışmalarına yönelik optimizasyonlar detaylı şekilde ele alınmıştır. Özellikle kalıp üretim süreçlerinde karşılaşılan verimlilik kayıpları, iş güvenliği riskleri ve operasyonel müdahale gereklilikleri, yapılan geliştirmeler sayesinde büyük ölçüde minimize edilmiştir. Yapılan iyileştirmeler kapsamında, CNC tezgâhlara ölçüm probu entegre edilerek takım uçlarında meydana gelen aşınma, kırılma veya tolerans dışı sapmaların otomatik olarak algılanması sağlanmıştır. Post processor yazılımı, işleme sırasında belirli periyotlarla takımı ölçüm pozisyonuna yönlendirmekte; takımın ölçümleri referans değerlerle karşılaştırılarak tolerans dışına çıkıldığında ofset değerleri otomatik işlem durdurularak operatör uyarılmaktadır. Bu sistem sayesinde, manuel kontrol ihtiyacı ortadan kaldırılmış, hem iş güvenliği hem de ürün kalitesi önemli oranda artırılmıştır. Geliştirilen post processor iyileştirmeleri yalnızca belirli bir CNC tezgâh markası ile sınırlı kalmayıp, farklı marka, model ve kontrol ünitesine sahip tezgâhlara uyumlu hale getirilmiştir. Bu kapsamda, makine tanıma algoritmaları sayesinde her bir tezgâhın spindle devri, ilerleme hızı, takım yolu formatı gibi parametreleri otomatik olarak belirlenmekte ve üretim başlamadan önce sistem tarafından optimize edilmektedir. Böylelikle operatör müdahalesine ihtiyaç duyulmadan, farklı tezgâhlar için özel işlem kodları üretilmekte ve çapraz uyumluluk sağlanmaktadır.

Anahtar Kelimeler: CNC tezgâhları, Post-processor optimizasyonu, Prob entegrasyonu, Güç kesintisi algılama

IMPROVING PRODUCTION EFFICIENCY THROUGH POST-PROCESSOR ENHANCEMENTS AND PROBE INTEGRATION IN CNC MACHINES

ABSTRACT

A transition has occurred from wheel rims produced from wooden materials in the past to today's aluminum alloy or composite structures. Throughout this evolution, numerous manufacturing methods have been developed and implemented, and studies on these processes continue. Currently, the majority of wheels used in the automotive industry are made of aluminum alloys and are produced using the low-pressure die casting method. There are many academic and industrial studies related to machining of casting molds and general subtractive manufacturing methods. In this study, optimization improvements carried out for next-generation enhancements integrated into post-processor software used in CNC machines are examined in detail. Productivity losses, occupational safety risks, and operational intervention requirements frequently encountered in mold manufacturing processes have been significantly minimized through the developments implemented. Within the scope of these improvements, a measurement probe was integrated into CNC machines, enabling automatic detection of tool wear, breakage, or out-of-tolerance deviations. During machining, the post-processor software directs the tool to the measurement position at specific intervals; tool measurements are compared with reference values, and when deviations exceed tolerance limits, the system automatically stops the operation and alerts the operator by updating the offset values. Through this system, the need for manual inspection has been eliminated, substantially enhancing both occupational safety and product quality. The developed post-processor enhancements are not limited to a specific CNC machine brand; instead, they have been adapted to machines of different brands, models, and control units. In this context, machine recognition algorithms automatically identify parameters such as spindle speed, feed rate, and toolpath format for each machine, and the system optimizes these parameters before production begins. Thus, without requiring operator intervention, customized machining codes are generated for different machines, ensuring cross-compatibility across the production line.

Keywords: CNC machines, Post-processor optimization, Probe integration, Power interruption detection

AISI H13 TAKIM ÇELİĞİNİN FARKLI DOLGU TELLERİ İLE KAYNAĞINDA MİKRO SERTLİK VE İMALAT SÜRESİ ARAŞTIRMASI

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ABSTRACT
İmalat parametrelerinin optimizasyonu ile üretim zamanlarının kısaltılması geçmişten günümüze önemli bir araştırma alanı olmuştur. Seri imalat yapan endüstriler için imalat zamanlarında saniyelerin bile önemli olduğu düşünülmektedir. Seri imalatta kalıplar ve kalıp bileşenleri kullanılmaktadır. AISI H13 takım çeliği ısıl işlemle ayarlanabilen özellikleri nedeniyle kalıp bileşenlerinin yenilenmesi ve tamirinde tercih edilmektedir. Kaynaklı imalatla yenilenen kalıp bileşenleri ancak işleme ve tesviye gibi imalat işlemleri sonrasında üretim hattına alınabilmektedir. Dolayısıyla, üretimin sürdürülebilirliği açısından kaynak, işleme ve tesviye sürelerinin araştırılması gereklidir. Ayrıca farklı dolgu telleri ile yapılan kaynak, farklı kaynak metali sertlik değerlerine neden olmakta ve sertlik artışı nedeniyle imalat süreleri uzayabilmektedir. Bu araştırmada, çelik numuneler 3 farklı dolgu teli kullanılarak birleştirilmiş, zımparalama ve parlatma işlemleri sonrasında Ana Metal, ITAB ve Kaynak Metalinin mikro sertlik ölçümleri yapılmıştır. Maksimum sertlik değeri Dolgu Teli 2'de 623 Vickers olarak kaynağın Isı Tesiri Altında Kalan Bölgesinde (ITAB) ölçülmüştür. Minimum sertlik değeri ise Dolgu Teli 3'te 249 Vickers olarak Kaynak Metalinde görülmüştür. Dolgu teli 1'de bu değerlerin arasında sertlik değerleri gözlenmiştir. Farklı dolgu telleri kullanılarak yenilenen AISI H13 takım çeliği kalıpların, kaynaklı imalat, işleme ve tesviye zamanları her tel için ölçülmüş ve mikro sertlik değerlerinin etkisi araştırılmıştır.
Anahtar Kelimeler: AISI H13 takım çeliği, imalat zamanı, mikro sertlik

Teşekkür: CMS Jant Makine San. A.Ş. (İzmir, Türkiye).

AN INVESTIGATION ON MICRO HARDNESS and PRODUCTION TIMES OF AISI H13 TOOL STEEL WELDING WITH DIFFERENT FILLER WIRES

ABSTRACT

Shortening the production time with optimising production parameters has been an important research field from past to today. Even seconds have been considered important in production time for industries which made serial production. Molds and mold parts have been used for serial production. AISI H13 steel is preferred for renovation and repair of mold parts due to its adjustable properties with heat treatment. Renovated mold parts can be taken to the production band after manufacturing processes such as machining and levelling. Thus, welding, machining and levelling times should be investigated for the sustainability of the production. Also, welding with different filler wires lead different weld metals which have different hardness values and production time can be increased due to high hardness values. In this study, steel specimens were welded with three different filler wires, micro hardness values were measured after grinding and polishing stages. Maximum hardness was measured as 623 Vickers at the Heat Affected Zone of FW2. Minimum hardness was seen as 249 Vickers in the Weld Metal of FW3. Moderate hardness values were observed for FW1. Welding, machining and levelling times were measured for AISI H13 tool steel molds which were renovated with using different filler wires and the effects of micro hardness values were investigated.

Keywords: AISI H13 tool steel, production time, micro hardness

Acknowledgment: CMS Jant Makine San. A.Ş. (İzmir, Türkiye).

BİNALARIN HAKİM PERİYOT TAHMİNİNDE ANALİTİK VE SAYISAL YAKLAŞIMLARIN DEĞERLENDİRİLMESİ

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ÖZET

Periyot, depreme dayanıklı yapı tasarımında ihtiyaç duyulan yapının önemli karakteristiklerindendir. Deprem mühendisliğinde temel bir parametre olan hâkim periyot, yapısal performansın öngörülmesi, tasarım spektrum eğrilerinin oluşturulması ve deprem etkisindeki mevcut yapıların durum değerlendirilmesi bakımından kritik bir rol üstlenmektedir. Bir binanın temel periyodu, yapının yüksekliği boyunca rijitlik ve kütlenin dağılımı ile ilişkilidir. Dolayısıyla deprem yükü etkisi altındaki binaların davranışı da, binaların rijitlik ve kütle özellikleri tarafından kontrol edilen yapının dinamik özelliklerine bağlı olmaktadır. Bu nedenle, bina periyodunun hesaplanmasıyla ilgili olarak yapılan çalışmalar literatürde önemli bir yer tutmaktadır. Bu çalışma da, binaların hakim periyodunun belirlenmesine yönelik literatürde yer alan analitik ve nümerik yöntemlerin kapsamlı bir değerlendirmesini sunmayı amaçlamaktadır. Bu çalışma kapsamında; ulusal ve uluslararası deprem yönetmeliklerinde sunulan ampirik periyot bağıntıları ile sayısal modal analiz yöntemleri karşılaştırmalı olarak değerlendirilmiş ve söz konusu yöntemler arasındaki uyum ile farklılıklar incelenmiştir. Ayrıca; kat sayısı, taşıyıcı sistem türü, malzeme özellikleri ve rijitlik dağılımı gibi bina özelliklerinin periyot değerleri üzerindeki etkileri tartışılmıştır. Çalışmadan elde edilen sonuçlar ile, hesaplama yöntemleri arasındaki farklılıkların sebepleri irdelenmekte ve tasarımcılar ile araştırmacıların uygun yöntem seçiminde yararlanabileceği kapsamlı çıkarımlar yapılarak öneriler sunulmaktadır.

Anahtar Kelimeler: Hakim periyot, Deprem, Dinamik karakteristik.

EVALUATION OF ANALYTICAL AND NUMERICAL APPROACHES IN ESTIMATING THE FUNDAMENTAL PERIOD OF BUILDINGS

ABSTRACT

The period is one of the important characteristics of a structure required in earthquake-resistant design. As a crucial parameter in earthquake engineering, the fundamental period plays a critical role in predicting structural performance, developing design spectrum curves, and assessing the existing structures under seismic effects. The fundamental period of a building is related to the distribution of stiffness and mass throughout the height of the structure. Therefore, the behavior of buildings under seismic loads depends on the dynamic characteristics of the structure, which are controlled by the stiffness and mass properties of the buildings. Consequently, studies related to the calculation of building periods are of significant importance in the existing literature. This study aims to provide a comprehensive evaluation of the analytical and numerical methods found in the literature for determining the fundamental period of buildings. Within the scope of this study, empirical period relationships presented in national and international earthquake codes were evaluated comparatively with analytical and numerical modal analysis methods, and the compatibility and differences between these methods were examined. Furthermore, the effects of building characteristics such as number of stories, type of structural system, material properties, and stiffness distribution on period values are discussed. The results obtained from the study examine the reasons for the differences between calculation methods and provide comprehensive conclusions and recommendations that designers and researchers can use to select the appropriate method.

Keywords: Fundamental period, Earthquake, Dynamic characteristic.

PARAFİN BAZLI FAZ DEĞİŞİM MALZEMELERİNİN YENİ NESİL NANOMALZEMELERLE İYİLEŞTİRİLMESİ

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ÖZET
Günümüzde hızla artan nüfus, mevcut enerjinin talebe yetişememesine ve fosil kaynaklar gibi yenilenemeyen enerji kaynaklarının hızla tükenmesine neden olmaktadır. Bu durum yenilenebilir enerji kaynaklarının (RES) kullanımını kaçınılmaz hale getirmiştir. RES'teki süreksiz ve değişken durumun üstesinden gelmek için üretilen enerjinin depolanması (ES) gerekmektedir. Bu, sistemlerin sürekli bir şekilde üretimlerine devam etmelerini sağlanmaktadır. Enerjinin sürdürülebilir şekilde kullanılması için üretimi kadar depolanması da çok önemlidir. Bu amaçla, gizli ısı depolama (LHS) yönteminde kullanılan faz-değişim-malzemeleri (PCMs), enerji depolama yoğunluklarının yüksek olması ile son yıllarda öne çıkmaktadırlar. Parafin, yüksek gizli ısı, geniş erime sıcaklığı, ekonomik olması, toksik olmaması ve kolay temin edilebilirlik gibi özellikleri ile bilinmektedir. PCM'ler içerisinde en çok tercih edilen organik-tabanlı bir malzemedir. Parafinin farklı erime sıcaklık aralıklarına sahip çeşitleri bulunmaktadır. Bu özellikleri ile elektronik cihazların termal yönetiminde, binaların ısı yönetiminde, sıcak su depolamada, gıda taşımada, güneş enerjili sistemler gibi farklı ES uygulamalarında tercih edilmektedir. Fakat, parafinin düşük ısıl iletkenliği, yüksek sızıntı oranları, düşük şekil stabilitesi, yüksek hacim değişimi gibi dezavantajları bulunmaktadır. Bu dezavantajların üstesinden gelebilmek için parafin FDM'sine karbon, seramik, metal- ve metal oksit-bazlı-nanomalzemeler ilave edilmektedir. Grafit ve grafen gibi karbon-bazlı-nanomalzemeler, düşük katkı oranlarında bile FDM'nin termal iletkenliğini, şarj ve deşarj hızını arttırmaktadırlar. Bor nitrür (BN) ve alümina (Al_2O_3) gibi seramik-bazlı-nanomalzemeler, FDM'nin termal ve kimyasal kararlılıklarını arttırarak uzun çevrimlerde ömürlerini uzatır. Ayrıca elektriksel yalıtkanlıklarının da artmasını sağlar. Bakır (Cu), alüminyum (Al), titanyum oksit (TiO_2) ve demir oksit (Fe_2O_3) gibi metal ve metal oksit-bazlı-nanomalzemeler ise çekirdeklenme merkezleri oluşturarak FDM'nin aşırı soğumasını azaltmaktadırlar. Uygun katkı oranı kullanılmadığında nanomalzemeler FDM içerisinde homojen olarak dağılamaz ve faz ayrışması meydana gelir. Ayrıca LHS kapasitesinde de düşmelere neden olur. Bu kapsamda, nanomalzemelerin ED uygulamasına göre seçilmesi sistemin verimliliğinin artmasını sağlayacaktır.
Keywords: Energy storage, PCM, Paraffin, Thermal efficiency, Nanomaterials

ENHANCING OF PARAFFIN-BASED PHASE CHANGE MATERIALS WITH NEXT-GENERATION NANOMATERIALS

ABSTRACT

The swiftly growing world population has resulted in an energy supply that can no longer satisfy rising demand, leading nonrenewable resources such as fossil fuels to deplete quickly. This has made the transition to renewable energy sources (RES) inevitable. To overcome the discontinuous and variable situation in RES, the produced energy needs to be stored. Energy-storage (ES) allows systems to run constantly while sustaining a balance between supply and demand. To this end, Phase-Change-Materials (PCMs), exploited in latent-heat-storage (LHS) systems, have gathered substantial attention in recent years due to their high ES density. Paraffin wax stands out as a widely used organic PCM, recognized for its high latent heat of fusion, broad melting point range, cost-effectiveness, non-toxicity, and commercial availability. With various grades exhibiting distinct phase-transition-temperatures, paraffin is utilized in diverse thermal management applications, including electronics cooling, building climate control, domestic hot water storage, perishable food transport, and solar thermal systems. Nevertheless, paraffin's adoption is restrained by inherent limitations such as low thermal conductivity, a pronounced tendency to leak in the liquid phase, poor shape stability, and significant volume change during phase transition. To mitigate these issues, nanomaterials—including carbon, ceramic, metal, and metal oxide variants—are introduced into the paraffin matrix. Carbon-based-nanomaterials like graphite and graphene significantly ameliorate the composite's thermal conductivity and charge-discharge rates, even at low loadings. Similarly, ceramic-based-nanomaterials such as boron-nitride (BN) and alumina (Al_2O_3) enrich thermal and chemical stability, thereby extending the PCM's service life over numerous cycles and improving its electrical insulation. In contrast, metal and metal oxide-based-nanomaterials (e.g., Cu, Al, TiO_2, Fe_2O_3) function primarily as nucleation agents, decreasing the degree-of-supercooling. Suboptimal loadings can lead to agglomeration and phase-separation, which degrades the LHS capacity. Therefore, the strategic selection of nanomaterials, tailored to the specific application, is vital for maximizing overall system performance.

Keywords: Energy storage, PCM, Paraffin, Thermal efficiency, Nanomaterials

NON-IMPREGNATION PROBLEM IN FRP ROPES

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ABSTRACT
The concept of civilization is a constantly evolving phenomenon, evolving as people adapt and improve their lifestyles and standards as they meet their own needs. Civil engineering is at the core of civilization because it is the engineering concept that provides the first step towards the continual development and transformation of shelter, the primary need for humankind, and also the first step towards uniting people and meeting other needs. Structures that have endured for centuries have always been maintained without major structural modifications to preserve the culture they reflect. In today's world, FRP materials are extensively used to strengthen structures. Thanks to the diverse contributions FRP materials offer in every geometry, they offer strengthening methods for all structural systems manufactured with past and present technologies. FRP fabrics, pipes, rods, profiles, and ropes all offer benefits in specific mechanical systems. FRP composite systems achieve their compositeness through the proper combination of fiber and epoxy materials. With a wide range of composite materials, it is crucial to achieve the theoretical strength and strengthening effect through proper application. Changes in the mechanical strength of FRP materials are also observed by adding nanographene to epoxy. This paper presents a study on the fracture and rupture mechanisms of composite rope elements produced using both conventional methods and those containing nanographene platelets, subjected to compression, tension, and bending tests, and on the production methods and impregnation status of the matrix material.
Keywords: Composite materials, Retrofitting, Epoxy, Nanographene, Impregnation, Engineering, Chemistry

PRODUCTION AND CHARACTERIZATION OF SILICON-BASED ACETONE SENSOR PREPARED UNDER ROOM CONDITIONS

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ABSTRACT

The porous silicon (PS) structure required for the fabrication of the device designed as an acetone vapor detector was formed on the n type crystalline silicon surface by electrochemical anodization with a HF-based electrolyte at constant time and current density. Ag paste was also applied to the surfaces of the GS/nSi structures under room conditions. The acetone vapor sensitivities of the Ag/GS/nSi structures were investigated with 50-250 ppm N_2 carrier gas over time. The junctions, which exhibit Schottky diode properties, produced a short-circuit current in acetone vapor without requiring an external power supply and exhibited gas sensor behavior. In our study, where the physical characterizations of the PS structure and the Ag paste/GS/nSi structure were performed, this structure, prepared under room conditions, was presented to the literature for the first time.

Keywords: Porous silicon, acetone, gas sensor

(The authors would like to thank YTU Scientific Research Projects Coordination for supporting this study with project number FYL-2025-7240.)

A COMPUTATIONAL STUDY OF BALLISTIC RESPONSE IN MULTI-LAYER TEXTILE PROTECTION SYSTEMS

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ABSTRACT

Since old times, mankind has continuously sought ways to protect itself from external threats. Depending on the type and severity of the attack, a wide variety of materials, including animal skin, copper, wood, and later steel have been used to construct protective armors. With the development of synthetic polymers in the 20th century, the field of personal and structural protection experienced a major transformation. Strong, lightweight fibers led to the rise of polymer-based composites and multilayer textile systems, which today form the backbone of modern ballistic protection, from body armor to vehicle panels and aircraft cockpit doors. In line with these technological advancements, this study investigates the ballistic impact behavior of soft, multilayer fabric armors through numerical simulation. The impact is modeled using a right circular cylindrical projectile. At the material level, the biaxial woven fabric is represented yarn-by-yarn using a discrete mass–spring–damper model with pin-joint connections. This approach allows the simulation to realistically capture how yarns interact, deform, and respond at high strain rates during impact. After the projectile strikes the fabric, the model tracks how the layers deform, how yarn velocities change over time, and how damage begins and spreads across the structure. These responses are visualized and analyzed using displacement fields, velocity histories, and strain contours generated throughout the simulation. To examine how material design influences performance, two fabric layers made from different fiber systems are combined in different stacking sequences. The ballistic effectiveness of each configuration is evaluated using key metrics such as back-face signature, residual projectile velocity and the pattern of damage.

Keywords: Composite body armors, ballistic impact, RCC, finite difference method.

A NOVEL TRIGONOMETRIC SHEAR DEFORMATION MODEL FOR PREDICTING THE THERMAL BUCKLING OF COMPOSITE STRUCTURES

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ABSTRACT
In this paper, a novel trigonometric shear deformation theory to examine the thermal stability analysis of functionally graded plates is presented. In this theory the distribution of transverse shear deformation is parabolic across the thickness of the plate by satisfying the surface conditions. Therefore, it is unnecessary to use a shear correction factor. The principle virtual works is used herein to extract equilibrium equations. The analytical solution is determined using the Navier method for a simply supported rectangular plate. The precision of this theory is verified by comparing it with the various solutions available in the literature.
Keywords: Thermal buckling analysis; FGM plates; composites.

A REVIEW ON STANDARD DESIGN PARAMETERS FOR RAMMED EARTH WALL CONSTRUCTION

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ABSTRACT

Rammed earth wall construction gained renewed attention in the modern world due to its low carbon footprint and sustainability in contrast to conventional masonry. It is prepared with compacted damp soil between temporary formworks. Although it is not a new invention and has been used for centuries, however in modern construction and wider practice a clear understanding and reliable guidelines of the standard parameters, including material properties, quality control, and the structural performance under different environmental and loading conditions are required. This research is a review on the findings of international standards and previous research work to highlight the essential parameters affecting the overall performance of rammed earth walls, including soil preparation, moisture levels, stabilizers, physical and mechanical properties. A natural rammed earth wall contains materials such as silt, clay, sand and gravel, among which the clay is considered as principal binder. The upper ranges of materials should be between 15-35% for clay, 30-80% for silt, and the mixture of sand and gravel varies between 20-80%. The proposed optimum moisture content of the mixture is about 10% that may have a density in the range of 2000-2300 kg/m^3. The recommended dosage of stabilizers, such as cement (OPC) ranging from 4-15%, and lime ranging between 6-12% of the soil mixture by dry weight. The minimum compressive strengths for sandy-gravel soil ranging between 2.7 to 6.9 MPa, silty soil between 2 to 6.2 MPa, and clayey soil ranges from 1.7 to 4.1 MPa. The rammed earth walls provide excellent thermal mass insulation properties for the house. The REW buildings should be designed as seismic resistant in earthquake-prone areas and having a monolithic dense subgrade or concrete for foundations. There is a minimum thickness requirement for interior and exterior walls in which for a one-storey building is 200 mm and 300 mm, while for a two-story building is 300 mm and 450 mm, respectively.

Keywords: Rammed earth, Design standards, Stabilizer, Mechanical properties, Thermal resistance, Seismic resistance.

IONIC-LIQUID GRAFTED $NIFE_2O_4$/G-C_3N_4 NNAOHYBRID FOR ULTRA-SENSITIVE AND SELECTIVE ELECTROCHEMICAL MELAMINE MONITORING

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ABSTRACT

In this study, we developed a conducting paper-based electrochemical biosensor (CPE) using 1-Butyl-3-methylimidazolium chloride ([BMIM][Cl^-]) and 1-Allyl-3-methylimidazolium chloride ([AMIM][Cl^-]) ionic liquids modified nickel ferrite ($NiFe_2O_4$) and graphitic carbon nitride (g-C_3N_4) nanohybrid (ILs@rGO-MoS_2) for the highly sensitive non-enzymatic detection of melamine. The stabilised Whatman filter paper has been modified using ILs@rGO-MoS2 nanohybrid to develop ILs@g-C_3N_4/$NiFe_2O_4$/CP electrode. The structural and morphological (FTIR, Raman, XRD, and FESEM-EDAX) results confirmed the successful development of the ILs@g-C_3N_4/$NiFe_2O_4$ nanohybrid and its uniform fabrication onto the CPE. The chronoamperometric results of ILs@g-C_3N_4/$NiFe_2O_4$/CPE indicate that it exhibits high conductivity, sensitivity, and a larger active surface area, which facilitates highly selective detection of Phenolic pollutants. The developed biosensor exhibited a wide linear range of 40.0 to 0.01 µM, with a low limit of detection of 2.12 µM and the sensitivity were 1.1723 µA μM^{-1} cm^{-2} for the detection of melamine. These findings demonstrate that the ILs@g-C_3N_4/$NiFe_2O_4$/CPE-based biosensor provides a low-cost, flexible, and environmentally friendly platform with excellent potential for detecting melamine in real sample analysis.

Keywords: Ionic Liquids, $NiFe_3O_4$@g-C_3N_4 nanohybrid, Biosensors, Melamine.

UTILIZING LOW-COST EGGSHELL AND COCONUT MIXTURES AS EFFICIENT ADSORBENTS FOR REMOVING LEAD AND CHROMIUM FROM TANNERY EFFLUENT

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ABSTRACT

This study evaluates the preparation, physicochemical properties, and heavy-metal adsorption performance of activated carbons produced from coconut shell and eggshell, and their composites, for treatment of tannery effluent. Activated carbons were produced by pyrolysis and chemical/steam activation, characterized by proximate analyses (moisture, ash, bulk density, pH), and applied at varying CS:ES ratios to 50 mL tannery wastewater samples under neutral conditions (pH 7) with 30 min contact times. Coconut-shell carbon (CS) exhibited the highest dual-metal removal, achieving up to 80.5% chromium and 85.5% lead removal, while eggshell carbon (ES) showed stronger Pb selectivity (up to 85.8% in certain composites). Composite adsorbents displayed synergistic and competitive behaviors: CS-rich blends favored Cr uptake, ES-rich blends enhanced Pb removal, and some mixed ratios produced improved Pb selectivity (e.g., sample F). Physicochemical data (ash 8.8–9.82%, bulk density ≈0.553–0.569 $g \cdot mL^{-1}$, moisture 6.2–8.7%, pH 7–7.5) indicate suitable handling and adsorption characteristics for aqueous treatment. The results demonstrate that low-cost, biomass-derived carbons and tailored composites offer effective, sustainable options for tannery wastewater remediation; the authors recommend regeneration studies, cost–benefit analyses, and pilot-scale trials to confirm field applicability.

Keywords: Chromium, lead, adsorbents, tannery wastewater, pollution, environment

EVALUATING WATER HYACINTH RESIDUE AS A VIABLE ALTERNATIVE TO CONVENTIONAL ORGANIC FERTILIZER

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ABSTRACT

Sustainable soil fertility management is vital for crop productivity in Bangladesh, particularly for smallholder farmers dependent on organic inputs. This study assessed the potential of composted water hyacinth (*Eichhornia crassipes*), an invasive aquatic weed, as an alternative to cowdung in cauliflower (*Brassica oleracea* var. botrytis subvar. cauliflora L.) cultivation under AEZ-14 (Gopalganj-Khulna Beels). A field trial was conducted using a randomized complete block design (RCBD) with four treatments: cowdung (5 t/ha), water hyacinth compost at 5, 8, and 11 t/ha. Agronomic parameters, yield, and soil nutrient dynamics were evaluated. Results revealed that water hyacinth compost at 11 t/ha significantly improved curd length (23.50 cm), diameter (50.13 cm), weight (534 g), and yield (22.25 t/ha) compared to cowdung (15.25 t/ha). Soil nutrient status post-harvest showed increased potassium and micronutrient availability, demonstrating water hyacinth's high nutrient content and its role in soil enrichment. The findings suggest water hyacinth compost is a cost-effective, eco-friendly alternative to conventional organic fertilizers, supporting sustainable crop production in nutrient-depleted soils.

ENHANCEMENT OF SAFETY AND ACCESSIBILITY IN THE DESIGN OF A PUBLIC TRANSPORTATION HUB FOR MINNA, NIGER STATE

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ABSTRACT

Inadequate safety and accessibility at Minna's motor transport hubs reflect wider infrastructural gaps in Nigerian cities. Observations reveal disorganized layouts and decaying facilities: for example, one study found most motor parks in Minna in disrepair, leaving commuters highly dissatisfied. Critically, basic accessible design is absent – one analysis noted that 80% of Nigerian construction projects omit disability planning entirely, compounding everyday barriers for mobility-impaired users. Inclusive design theory emphasizes that wellplanned internal circulation and safety features are essential for all. Indeed, embedding universal design in transit facilities "allows everyone to enjoy spaces on equal terms" and makes travel safer and easier for users of all ages and abilities. For this study, a mixed-methods approach was employed, combining site surveys, stakeholder interviews, and observational audits to systematically map pedestrian and vehicular flows and user experiences at Minna's main transport hub. Findings reveal chaotic spatial organization (e.g. waiting areas encroaching on parking), missing accessible elements (no ramps or tactile pathways), and critical safety lapses (inadequate lighting, no surveillance). For instance, many commuters reported waiting in their vehicles under open sky due to absent sheltered lounges – a circumstance previously described as "unpleasant" in Minna parks. These operational deficiencies underscore the urgent need for comprehensive redesign of the hub. We propose a context-sensitive design framework to reconceive the hub as an inclusive civic space. The framework reorganizes the station into clearly defined zones (drop-off, boarding, waiting) with barrier-free circulation routes and enhanced wayfinding, coupled with robust safety infrastructure (ramps, tactile guides, welllit shelters, CCTV). By foregrounding universal design principles, it aligns with Nigeria's disability-rights commitments (e.g. UNCRPD ratification) and translates them into practical station design guidelines. The framework offers urban planners, policymakers and architects an actionable model for inclusive transport hub design, advancing equitable mobility and social inclusion in the Nigerian context.

Keywords: Public transportation hub, accessibility, safety, universal design, Minna, inclusive urban design

SEEING AND SELLING THE CITY: VISUAL CONSUMPTION AND THE EROSION OF THE 'RIGHT TO THE CITY'

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ABSTRACT
Critically this paper examines, the increasing power of visual consumption in shaping the modern urban setting and its consequences of allegedly weakening the right to the city coined by Henri Lefebvre. The study investigates the modifications occur to perceptions of space, identity and belonging through the circulation of commodified imagery, through visual analysis, qualitative interviews, and quantitative surveys in multiple case studies across urban contexts. Results show that the visual representations are increasingly driven by aesthetics rather than authenticity and local narratives in more ways than not are placed on the periphery thus promoting the socio-spatial inequalities. Those who live in the city complain that they do not relate to urban visions sold to them on the market, instead, experiencing alienation and being deprived of the ability to construct their urban futures. In addition, the study also focuses on the emergence of grassroots movements that oppose the visual hegemonies and the effort of reclaiming representational and physical urban space. The article ends by urging the adoption of inclusive models of urban governance that are capable of challenging domination of visual commodification and joining together to enforce collectivity, rights to engage, producing, using, and shaping urban space.
Keywords: Visual Consumption; Right to the City; Urban Commodification; Public Space Representation; Grassroots Urban Resistance.

ROLE OF WOMEN IN SUSTAINABLE DEVELOPMENT: CHALLENGES AND OPPORTUNITIES

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ABSTRACT

Women and Development is a significant topic in social sciences and development studies that focuses on the role, status, and participation of women in the process of societal growth and progress. In the past, women's roles were often overlooked, and their contributions were mostly confined to family responsibilities. However, with the expansion of education, awareness, and cultural as well as economic transformations, women have emerged as key pillars of development. Sustainable development cannot be achieved without the effective participation of women in social, economic, cultural, and political fields. This study examines the concept of women and development, the historical evolution of women's participation in development, and the existing barriers such as gender discrimination, inequality of opportunities, weak legal protections, and traditional cultural attitudes. It also highlights the importance of empowering women through education, employment, political participation, and access to resources. Research shows that countries prioritizing gender equality and women's involvement perform better in human, economic, and social development indicators. In conclusion, true development can only be realized when women actively participate as decision-makers in society, and national policies are designed and implemented based on principles of gender justice and equal opportunity.

Keywords: Women and Development, Women's Empowerment, Sustainable Development, Social and Economic Participation

ENHANCING PRODUCTIVITY AND PROFITABILITY IN ONION FARMING: INSIGHTS FROM FARMER PRACTICES AND CONSTRAINTS IN BANGLADESH

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ABSTRACT

Onion (Allium cepa) is a vital cash crop in Bangladesh, yet farmers continue to experience production and marketing challenges that limit profitability. This study explored cultivation techniques, storage systems, extension support, and farmers' perceptions with a special focus

on cost and income-related factors. Using data from 67 growers collected through a structured questionnaire, the analysis revealed that onion cultivation is concentrated in sandy-loam and clay soils. Despite its importance, farmers overwhelmingly relied on traditional storage methods, resulting in significant post-harvest losses and increased production costs. Respondents emphasized the need for modern training opportunities, better-quality seeds, improved irrigation infrastructure and accessible credit to reduce risks and enhance returns. Good seed quality and high-yielding varieties were identified as key drivers of productivity, supported by the use of organic fertilizers. Extension services played a major role with most farmers receiving guidance from agricultural officers, although limited market stability and insufficient credit facilities continued to hinder investment in improved practices. The study highlights the need for strengthened farmer capacity-building, wider availability of quality seed, affordable financial support and modern storage solutions to increase profitability, reduce dependence on imports and ensure sustainable growth of the onion sector in Bangladesh.
Keyword : Onion farming, Post harvest losses, Quality seed, Extension services, Profitability and Sustainability.

STRATEGY FOR SUSTAINABLE NUTRITIONAL FORTIFICATION OF SUMMER SALAMI VIA OILSEED PRESS CAKES

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ABSTRACT

Agro-industrial by-products have become an important resource in modern food innovation, driven by growing consumer interest in nutritious and environmentally sustainable products. Among these by-products, press cakes obtained from oil extraction, particularly those derived from pumpkin and walnut seeds, are known for their rich nutritional composition, including proteins, dietary fiber, essential fatty acids, and antioxidants. This study explores the incorporation of walnut and pumpkin seed press cakes into salami formulations to develop novel, nutrient-rich products that meet consumer demands and support sustainable practices. In this study, five salami formulations were developed as follows: a control summer salami (SSc), SS3%pp, summer salami prepared by substituting 3% cured meat with pumpkin press cake powder, SS5%pp, summer salami prepared by substituting 5% cured meat with pumpkin press cake powder, SS3%wp, summer salami prepared by substituting 3% cured meat with walnut press cake powder, and SS5%wp, summer salami prepared by substituting 5% cured meat with walnut press cake powder. The different salami formulations were evaluated for their physicochemical properties, energy value, texture profile, color attributes, and sensory characteristics. The incorporation of press cake powders into summer salami resulted in a product with a more complex lipid profile enriched in unsaturated fatty acids, increased fiber and mineral content, and slight textural changes, without compromising sensory quality. Incorporating press cake powders into salami enhanced its nutritional value and lipid profile without raising production costs. The approach maintained product quality while promoting sustainability by valorizing agro-industrial by-products, supporting a circular economy. These findings demonstrate that press cake inclusion is a viable strategy for developing nutrient-enriched, responsibly produced meat products that meet consumer expectations.

Keywords: summer salami, pumpkin press cake powder, walnut press cake powder

SPATIOTEMPORAL CLIMATE-INDUCED MIGRATION HOTSPOTS IN SOUTH ASIA: A GEOSPATIAL-HUMANITARIAN ENGINEERING APPROACH USING SATELLITE REMOTE SENSING AND SOCIOECONOMIC INDICATORS IN BANGLADESH

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ABSTRACT
One of the most significant challenges facing humanity in South Asia is migration caused by climate change. By 2050, 9.6 million people in Bangladesh alone are expected to be displaced as a result of these changes. A major obstacle to response planning and adaptation of the affected areas is the lack of systematic designation of migratory hotspots, despite the fact that the prevalence of climatic disasters such as floods, cyclones, and droughts has been documented in detail. In order to identify and analyze climate-induced migration locations in Bangladesh's administrative units, the study suggests a multi-factor Migration Risk Index (MRI) that integrates satellite-derived indicators of climatic risks, socioeconomic exposure measures, and nightlights-based development proxies. Five independent climate and environmental indices for the years 1994 to 2024 across Bangladesh's administrative divisions were created using Google Earth Engine (GEE): (1) Sentinel-2 synthetic aperture radar (SAR) data-based flood frequency; (2) Landsat 8 NDVI trend analysis mapping vegetation stress areas; (3) CHIRPS rainfall anomalies cutting drought areas; (4) flood exposure derived from the digital elevation model (DEM); and (5) NOAA VIIRS nightlight trends as a proxy for economic activity. Following normalization (0-1 range). The population census 2021 was used to collect data for each district, resulting in population-weighted MRI scores. Trends in population density and economic displacement signals from sources based on nightlights were used in the validation procedure.
Keywords: Climate-induced migration, remote sensing, satellite-based, migration risk index, Bangladesh;

PHYSIO – BIOCHEMICAL RESPONSES OF WHEAT (*TRITICUM AESTIVUM* L.) TO EXOGENOUSLY APPLIED HYDROGEN PEROXIODE AND SUCROSE UNDER SALT STRESS

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ABSTRACT

A pot experiment was conducted in Botanic Garden of Government college university Faisalabad to assess the responses of two differently salt tolerant wheat varieties (Dilkash and Urooj) to exogenously applied Sucrose and H_2O_2 as seed priming under saline stress. Seeds of two wheat varieties were soaked in sucrose (0mM, 25mM) and hydrogen peroxide (0mM,1mM) for 16 hours with Nacl salt levels (0mM and150 mM). Salt stress markedly decreased the growth attributes, imbalance nutrient and yield reduction while enhanced the level of H_2O_2, malonaldehyde accumulations of osmolytes and regulated antioxidative defense mechanism in both wheat varieties. The seed priming with signaling molecules in both wheat varieties enhanced the content of enzymatic as well as non-enzymatic antioxidants. Seed priming with signaling molecules caused a significant improvement in k+/Na+ in both wheat varieties but more improvement was in Dilkash. In conclusion, Sucrose and Hydrogen peroxide pre-sowing treatments induced salt tolerance with improved chlorophyll content, water relations, accumulation of osmolytes, antioxidative defense mechanism and improved yield.

OBSERVING NESTING BIRDS ON THE SOUTH KHANGAI PLATEAU IN SPRING

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ABSTRACT

The South Khangai Plateau is a vast, sloping plateau located at the foot of the southern macroslope of the Main Khangai Range and gradually descending toward the Gobi Lakes Valley, where it drops off into a steep escarpment. The plateau is crossed by three major rivers—the Baidrag, Tuin, and Taats—whose headwaters lie in the Main Khangai Range. These rivers flow through deep but wide valleys with well-defined terraces; in a few places, the valleys narrow, forming gorges. The main part of the plateau surface lies at absolute altitudes of 1250-2100 m, but individual mountains and ridges rise up to 2700 m above sea level. The Tuin River is part of the Central Asian Basin, and its surroundings are located in the Ulziyt soum of the Bayankhongor aimag. Ulziit soum is located 18.6 kilometers east of the aimag center. The field study area is located in the Bayanburd is located approximately 7 kilometers from the center of Ulziit soum. It is located approximately 1 kilometer northeast of the Tuin River basin. The primary research method was foot-based route surveys, covering a total of over 30 km. The total area covered was 49,88 ga. The birds were observed on April 9, 2024. Bird counts were conducted using a ZESS CONQUEST HD 8*32 binoculars and a SONY DSC-HX400 digital camera with 20.4 megapixels. Bird names in the list are based on the summary by S. Gombobaatar, 2019, and the faunal genetic structure by Stegmann, 1938. In the Bayanburd (western south part of Mongolia) 19 species of birds belonging to 6 orders, 9 families and 17 genera are recorded. The dominant ecological group of the avifauna of the Bayanburd is campophiles, which account for 9 (47%) species; 5 (26%) are dendrophiles, 3 (17%) species are sclerophylls. In wetland areas 2 (10%) species limnophiles are found. The avifauna of Bayanburd, where the mining area is located, is widely represented by mid-latitude species. According to the ornithogeographic division of B.K. Stegman (1938), they belong to the following fauna types: Mongolian 47% (n=9), Transpalearctic 21% (n=4), Mediterranean 11% (n=2), European 11% (n=2), Tibetan 5% (n=1) and Arctic 5% (n=1). During the observation, 3 species of birds (*Eremophila alpestris*, *Oenanthe isabelline*, *Petronia petronia*) were frequently encountered. The *Eremophila alpestris* is the dominant species in the Bayanburd region. Three bird species found in the spring in the Bayanburd area of the Tuin River basin of Bayankhongor aimag are listed in Appendix II of the CITES Convention: the steppe eagle (*Aquila nipalensis*), the cineteous vulture (*Aegyrius monachus*) and the bearded vulture (*Gypaetus barbatus*). Thus, in the western part of the country nesting species include the steppe eagle, cinereous vulture, northern raven, horned lark, isabelline wheatear and rock sparrow. According to Bold, steppe eagle (*Aquila nipalensis*) begins nesting in the Khentii mountain region in early May. However, during our research in this area, which forms the northern boundary of South Khangai Plateau, egg laying was observed as early as April 9. The bearded vulture (*Gypaetus barbatus*), who live in the mountains around Bayanburd, eat Mongolian gerbil (*Meriones unguiculatus*).

CLASSIFICATION OF MULTIFIDUS SURFACE ELECTROMYOGRAPHY FOR LOW BACK PAIN DETECTION: SUPERIOR PERFORMANCE WITH FREQUENCY-DOMAIN FEATURES

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ABSTRACT

Low back pain (LBP) affects millions worldwide and lacks objective diagnostic biomarkers. This study aimed to evaluated surface electromyography (sEMG) features from bilateral multifidus muscles to discriminate LBP patients from healthy controls during trunk movements. EMG signals from 22 participants (12 healthy, 10 LBP) were recorded during flexion and extension tasks. After preprocessing (bandpass Butterworth and notch filtering), signals were segmented, rectified, smoothed, and characterized using time-domain, frequency-domain, and time–frequency descriptors. Seven classifiers—Support Vector Machine, K-Nearest Neighbors, Decision Tree, Linear Discriminant Analysis, Random Forest, Logistic Regression, and Extreme Gradient Boosting—were trained and evaluated via stratified 5-fold cross-validation. Frequency-domain features consistently outperformed time-domain and time–frequency descriptors. Random Forest achieved 86% accuracy using combined frequency features for extension tasks, while Decision Tree reached 85% accuracy on the same feature set. Extension movements yielded superior discrimination compared to flexion (86% vs. 78% accuracy). ROC-AUC analysis confirmed strong classifier discrimination (AUC >0.80 for optimal models). These findings establish multifidus sEMG frequency signatures as discriminative biomarkers for LBP detection. Systematic feature selection combined with ensemble classifiers effectively identifies abnormal muscle activation patterns associated with LBP. The clinical utility of frequency-based sEMG analysis warrants further investigation for objective, non-invasive LBP diagnosis in clinical settings, rehabilitation monitoring, and wearable health systems.

Keywords: Surface electromyography, Low back pain, Multifidus, Multi-domain analysis, Machine learning.

SMART BLIND ASSISTANT GLASSES

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ABSTRACT

Smart Blind Assistant Glasses aim to enhance the mobility, safety, and independence of visually impaired individuals by integrating modern computer vision, deep learning, and assistive technologies. These glasses are designed to detect and recognize real-world objects, obstacles, and people in the environment using advanced object detection algorithms such as YOLO and deep neural networks. The system provides real-time audio feedback, allowing the user to perceive surroundings through auditory cues rather than sight. Spoken instructions such as “person ahead,” “door on right,” or “stairs down” guide the user for safe navigation. The prototype utilizes a camera module, microcontroller, and audio output system to process live video feeds and convert them into descriptive audio information. Techniques like image processing, object tracking, and distance estimation are used to ensure accurate detection and timely alerts. The dataset used for training includes diverse real-world objects and environmental conditions to enhance system reliability. Experimental results show that the model achieves efficient object recognition with real-time response and minimal latency, ensuring smooth navigation. The integration of YOLO-based detection improves accuracy compared to traditional methods. Future work aims to include GPS-based navigation, voice-command control, and edge AI optimization for standalone wearable operation, making the system more intelligent and user-friendly for visually impaired individuals.

Keywords: Assistive Technology, Object Detection, Computer Vision, Deep Learning, Audio Feedback, Real-time Navigation.

SATELLITE IMAGE SEGMENTATION FOR URBAN PLANNING

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ABSTRACT

Satellite image segmentation plays a vital role in urban planning by providing detailed insights into land use, infrastructure, and environmental conditions. With rapid urbanization, traditional manual mapping methods are no longer efficient for large-scale city analysis. This project leverages deep learning techniques, specifically the U-Net model, to perform automated and accurate segmentation of high-resolution satellite images. The U-Net architecture, known for its encoder-decoder structure with skip connections, enables precise pixel-level classification of satellite imagery. Using datasets such as DeepGlobe Land Cover, the model is trained to identify and categorize key urban features including buildings, roads, vegetation, and water bodies. The preprocessing steps involve image enhancement, noise removal, and annotation to improve data quality and model performance. By integrating the segmented results into Geographic Information Systems (GIS), urban planners can visualize spatial layouts, monitor land-use changes, and assess environmental impacts. This approach supports smart city development, resource management, and disaster preparedness by enabling data-driven decisions. The U-Net model's efficiency and high accuracy make it a powerful tool for sustainable urban development and real-time city monitoring.

Keywords: Satellite Image Segmentation, Urban Planning, Deep Learning, U-Net Model, Semantic Segmentation, Smart City Development, GIS Integration, Land Use Classification, Remote Sensing, Sustainable Urban Development

DINUCLEAR METAL COMPLEXES AS RECYCLABLE CATALYSTS IN ORGANIC SYNTHESIS

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ABSTRACT

New dinuclear vanadium(V) Schiff base complexes were successfully synthesized and characterized for application as recyclable catalysts in organic synthesis. Two water-soluble oxo-bridged complexes, $[(L1H)VO(\mu\text{-}O)]_2$ (C1) and $[(L2H)VO(\mu\text{-}O)]_2$ (C2), were prepared through the reaction of $VOSO_4$ with tetradentate Schiff base ligands under reflux in methanol. Their catalytic activity was investigated in the oxidation of olefins using water as an environmentally friendly reaction medium and different oxidizing agents. The dinuclear complexes demonstrated excellent catalytic efficiency, high product yields, and remarkable stability over multiple catalytic cycles. These results highlight the potential of oxovanadium(V) dinuclear systems as efficient and reusable catalysts for green organic transformations.

Keywords: Green catalysis ; Olefin oxidation; Vanadium(V) complexes

DETERMINISTIC AND PROBABILISTIC ANALYSIS OF WEDGE SLIDING POTENTIAL IN ROCK SLOPES

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ABSTRACT

Kinematic analysis is a widely used method for assessing the discontinuity controlled stability in rock slopes. The method evaluates planar, wedge, and toppling failure mechanisms. Risks associated with different failure types are analyzed using stereographic projections. The dip and dip direction of the slopes, along with the distribution and intersections of discontinuity planes, are considered in the analyses. Wedge sliding, one of these failure mechanisms, occurs when at least two discontinuity planes or sets intersect unfavorably, forming a wedge-shaped rock block that slides along the intersection line. In this study, the wedge sliding potential of the western slopes of the abandoned quarry in Kartal, Istanbul, was investigated. Kinematic analyses were conducted on four slopes, designated as S-1, S-2, S-3, and S-4. The results indicated that failure probabilities ranged from 14.3% to 49.3%, suggesting that the slopes are susceptible to wedge sliding. The risks for each slope were evaluated using deterministic and probabilistic approaches, based on the calculated failure probabilities and factors of safety. To this end, the dominant orientations of discontinuity sets that may contribute to wedge sliding were determined by employing the Fisher distribution and Goodman's graphical approach. These dominant discontinuity sets, located within the critical zone on the stereonet, were analyzed for each slope under static and dynamic conditions. Under static conditions, the number of dominant intersecting discontinuity sets that fell below the required factor of safety criterion ($FoS \geq 1.5$) was determined to be three, two, five, and two, corresponding to slopes S-1 to S-4. Dynamic analyses indicated that earthquake-induced effects increased the count of the critical dominant discontinuity sets. Under dynamic conditions, these intersecting sets that did not meet the required factor of safety ($FoS \geq 1.0$) increased to four, three, seven, and three, respectively. Both deterministic and probabilistic analyses revealed a reduction in the calculated factors of safety under dynamic conditions. On average, the rate of decrease ranged from 26.2% to 55.6% compared to static conditions. Consequently, the study demonstrated that some dominant discontinuity sets of the slopes, which pose no significant risks under static conditions, may reach critical states during an earthquake and cause wedge sliding.

Keywords: Deterministic analysis, factor of safety, probabilistic analysis, rock slope, wedge sliding.

COMPARATIVE ASSESSMENT OF GROWTH PERFORMANCE AND SURVIVAL RATE OF MONO-SEX AND MIXED-SEX NILE TILAPIA (*OREOCHROMIS NILOTICUS*) IN CAGE CULTURE SYSTEMS: EVIDENCE FROM SOUTHERN BANGLADESH

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ABSTRACT

An experiment was conducted in a cage culture system over 90 to observe the growth and survival rate of mono-sex and mixed-sex Nile tilapia at Bhandaria, Pirojpur district of Bangladesh. The experiment was carried out with three treatments containing three replications. In treatment 1 (T_1) mono-sex tilapia, in treatment 2 (T_2) mixed-sex tilapia, and treatment 3 (T_3) mono-sex + mixed-sex (50:50) tilapia were stocked. During the study period, key water quality parameters were measured fortnightly and found to be within the acceptable range for aquaculture. At the beginning of culture period, the average individual weight (±SD) was 9.5 ± 1.33g, 10.02 ± 1.75g, and 9.85 ± 1.82g in T_1, T_2, and T_3 respectively with similar stocking density (5 fish/square feet). Fish were fed commercially available floating fish feed (28% protein) with 6% body weight at the beginning of experiments and gradually reduced to 3%. The Mean final weights were 262.78 ± 12.40g, 245.30 ± 13.32g, and 252.14 ± 15.25g in T_1, T_2, and T_3 respectively. However, there were no significant ($P>0.05$) differences observed in mean final weights among T_1, T_2, and T_3. The specific growth rate (SGR) was significantly ($P<0.05$) higher in T_1 (3.22 ± 0.02), followed by T_3 (3.12 ± 0.03) and T_2 (2.99 ± 0.09). No significant difference ($P>0.05$) was observed among treatments in case of total production. The benefit-cost ratio (BCR) was calculated as 1.15, 1.13, and 1.14 in T_1, T_2, and T_3, respectively, which did not differ significantly. The present findings indicate that the production of mono-sex and mixed-sex Nile tilapia has been successful. When mono-sex Nile tilapia are unavailable to farmers, they can culture mixed-sex Nile tilapia in cages up to the spawning period (approximately 3-4 months), thereby improving the economic situation of rural farmers as an alternative source of income.

Keywords: Mono-sex, Mixed-sex, Nile tilapia, cage culture, growth performance.

SYNTHESIS, CHARACTERIZATION, AND COMPUTATIONAL INVESTIGATION OF 2,5-BIS(2-METHYL-1H-BENZIMIDAZOL-5-YL)-1,3,4-OXADIAZOLE: QUANTUM CHEMICAL ANALYSIS, ADME PREDICTION, MOLECULAR DOCKING, AND MD-BASED CORROSION STUDY FOR PHOTONIC AND THERAPEUTIC APPLICATIONS"

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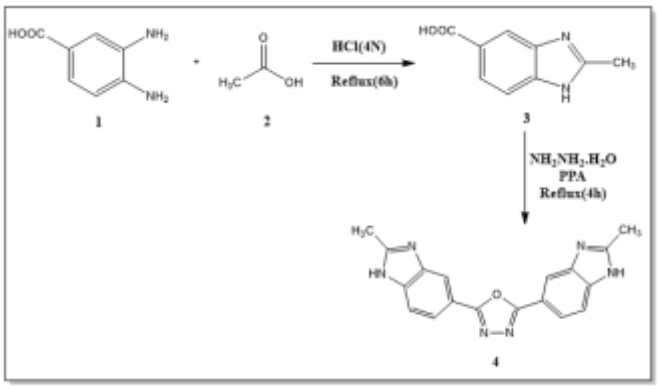
ABSTRACT
This study presents the synthesis and characterization of 2,5-bis(2-methyl-1H-benzimidazol-5-yl)-1,3,4-oxadiazole, using ^{1}H NMR, ^{13}C NMR, mass spectrometry and FTIR-ATR infrared spectroscopy. Quantum chemical analysis revealed that P1 possesses a balanced electrophilic–nucleophilic profile, enabling interactions with diverse biological targets. Its HOMO–LUMO gap and electronic stability suggest potential applications in photonic devices. ADMET predictions indicated favorable pharmacokinetics and overall drug-likeness. Molecular docking demonstrated high binding affinities toward anticancer, antibacterial, and antifungal proteins, with P1 reproducing reference ligand binding modes while forming additional stabilizing contacts. Molecular Dynamics simulations captured the thermal motion and conformational flexibility of P1 on the Fe(110) surface, while Monte Carlo simulations identified energy-minimized, compact adsorption conformations. Both approaches confirmed thermodynamically favorable chemisorption, stabilized by direct surface interactions and solvent/ionic contributions. Together, these findings highlight P1 as a dual-purpose scaffold, combining selective biological activity, favorable electronic properties, and strong surface interactions. This integrated computational study supports its potential for both therapeutic development and optoelectronic application.

Keywords: Synthesis, Characterization, 1,3,4-oxadiazole, DFT, Reactivity, ADME/Toxicity, Molecular Docking, Monte Carlo, Molecular Dynamic



FERMENTATION EFFICIENCY OF RICE BRAN, RICE POLISH, AND DE-OILED RICE BRAN FOR NUTRITIONAL UPGRADING AND BIOETHANOL PRODUCTION

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ABSTRACT

Background: Rice Bran (RB) and Rice Polish (RP) are by-products of rice milling industry where further oil extraction from RB produces De-oiled Rice Bran (DORB). All of these by-products are often underused because they contain anti-nutritional factors (ANFs), have high fiber content, and limited nutrient availability. This study aimed to improve the nutritional potentiality through yeast fermentation. Methods: Three rice by products (RB, RP and DORB) were employed in a 2×3×9 factorial experiment with Baker's yeast (*Saccharomyces cerevisiae*) at 1.0 and 2.0% level, with three moisture levels (40, 50, 60%) and 9 times (0, 6, 12, 18, 24, 30, 36, 42, 48hours), incubated at 39°C in 100ml glass syringe. The fermentation efficiency was measured by cumulative gas production, ethanol yield, change in proximate composition, and availability of phosphorus (AvP.). Results: Fermentation of RB was maximum, with 2932ml/100g DM gas at 6h and 3.49g/100ml ethanol at 48h at 60% moisture level and 2.0% yeast. Its crude protein (CP) was raised by 23.1%, crude fiber (CF) was lowered by 20.1%, ether extract (EE) doubled nearly, metabolizable energy (ME) by 27.0%, and AvP. 0.27 to 0.42. RP was found as moderately fermentable by 713ml/100g DM gas and 1.45g/100ml ethanol, whereas nutritional improvement was noticed with an 18.2% reduction of CF, 66% increase in EE, 9.5% increase in ME, and AvP. from 0.95 to 1.26. DORB was least fermentable but showed considerable nutritional improvements, including a 15.6% improvement in CP, 18.9% reduction in CF, 294% increase in EE, 22% increase in ME, and a change in AvP. from 0.82% to 1.02%. Conclusion: Fermentation significantly improved the nutritional potential of RB, RP, and DORB, with RB having the highest protein, ME, and AvP. Though RB was most fermentable, RP was partially improved, whereas DORB, despite low fermentability, had high protein, fiber removal, and phosphorus bioavailability.

Keyword: Bio-ethanol, De-oiled rice bran, Fermentation, Nutrition, Rice bran, Rice Polish.

LOW-TEMPERATURE CATALYTIC GRAPHITIZATION FOR HIGH PERFORMANCE CARBON MATERIALS

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ABSTRACT
This work focuses on developing low-temperature catalytic routes to convert renewable lignocellulosic biomass into advanced carbon materials with graphitic or graphene-like structures. The study relies on strategies designed to guide carbon reorganization during carbonization. By using catalysts that lower the activation energy, effective graphitization can be achieved at temperatures significantly lower than those required by conventional methods. The goal is to produce graphitic or graphene-like carbons with tunable porosity, heteroatom doping, and, when needed, metal functionalities, in order to meet the growing demand for sustainable graphite materials in fields such as energy storage and electronics. Special attention is given to how preparation conditions influence the final properties, to better understand the key parameters governing performance. Overall, this research aims to establish a tunable and energy-efficient approach for producing next-generation porous carbons from sustainable biomass resources
Keywords : Graphite, Graphene, Biomass.

NEO FACE - AI-POWERED FACE RECONSTRUCTION

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ABSTRACT
3D face reconstruction using Convolutional Neural Networks (CNNs) is an emerging technique that enables the generation of accurate three-dimensional facial models from single or multiple two dimensional images. This process is crucial for applications in security, animation, virtual reality, and human–computer interaction. Traditional 3D modeling methods require specialized hardware such as depth sensors or multi-view camera setups, which are expensive and time-consuming. In contrast, CNN-based methods leverage deep learning to infer 3D geometry directly from 2D image data. These networks learn hierarchical features that capture facial structure, shape, and texture. By training on large datasets, CNNs can generalize well to variations in pose, lighting, and expression. This makes the approach robust and suitable for real-time applications. The proposed system typically consists of a feature extraction module followed by a regression or decoder network that reconstructs the 3D facial mesh or depth map. Loss functions are designed to minimize geometric errors, photometric inconsistencies, and sometimes perceptual differences between the predicted and ground truth models. Data augmentation techniques are applied to enhance performance on diverse real-world conditions. The reconstructed faces can be refined using post-processing algorithms for improved accuracy. Integration with 3D Morphable Models (3DMM) further enhances reconstruction quality. This CNN-based approach significantly reduces computational cost while maintaining high fidelity in facial details. As a result, it offers a scalable and efficient solution for various biometric and multimedia applications.

Keywords: 3D Face Reconstruction, Convolutional Neural Networks (CNNs), Deep Learning, Feature Extraction, 3D Morphable Model (3DMM)

SUSTAINABLE MILLET FOR FOOD AND FEED PRODUCTION IN SEMI-ARID CLIMATES: UTILIZING TRICKLING FILTER-TREATED WASTEWATE

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ABSTRACT

Millets are significant grains worldwide, yet they remain underutilized. They are rich in nutrients and health-beneficial phenol compounds, such as phenol acids, flavonoids , and tannins, which contribute to high antioxidant activity. The presence of these photochemical can improve human health by, for example, reducing cholesterol levels .The nutritional and phenol content varies between millet species. Finger millet, for instance, possesses a more abundant and diverse phenol profile compared to pearl millet. This diversity indicates that the specific type of millet is an important consideration when selecting it for food or feed .Given the high demand for maize across multiple industries, millets offer a viable alternative to ease this pressure. Studies show that substituting maize with pearl or finger millet in animal diets has a positive impact on livestock performance. For example, incorporating 50% or more pearl millet into broiler diets does not adversely affect growth or egg production. Beyond animal feed, millet grain is also being used in a variety of foods and traditional beverages. This review aims to provide comprehensive insight into the nutritional and phenol properties of millets and their impact on both human and livestock health .In a separate five-month study, we investigated the use of raw urban wastewater (RWW) and treated wastewater (TWW) from a Trickling Filter process for irrigating millet, using well water (WW) as a control. We assessed the crop's agro physiological and biochemical properties .The results showed that irrigation with both RWW and TWW led to the highest millet productivity and leaf area compared to WW. Macro-elements like total phosphorus (TP), total Kjeldahl nitrogen (TKN), and potassium (K) were also higher in plants irrigated with RWW. In contrast, plants irrigated with well water accumulated more calcium (Ca), sodium (Na), and magnesium (Mg).Furthermore, the use of treated urban wastewater improved the soil's physicochemical properties and fertility compared to well water, thereby enhancing crop productivity.

HARVESTING URBAN WISDOM: A POLICY BLUEPRINT FOR SUSTAINABLE NIGERIA INSPIRED BY LATIN AMERICA'S TALES AND ECOLOGICAL ECHOES

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ABSTRACT

Nigeria's economic journey bears striking similarities to Latin America's past, with an over-reliance on raw material exports and weak institutions hindering growth. Our research draws valuable lessons from Brazil, Argentina, and Chile to propose a policy blueprint for a sustainable Nigeria. We recommend modernising agriculture, embracing sustainable mining practices, and adopting smart urbanisation strategies. These measures, coupled with economic diversification, climate action, and transparent governance, are vital for Nigeria's long-term resilience. The Nigerian economy can learn from Latin America's experiences, such as Brazil's innovative agribusiness sector and Chile's responsible mining model. By adopting climate-smart agriculture and agro-processing, Nigeria can enhance food security and boost exports. Moreover, smart planning, investment in public transport, and green infrastructure can help address urbanisation challenges. Our blueprint provides policymakers with actionable recommendations, including mechanised commercial farming, R&D investment, and transparent licensing for mining. By implementing these strategies, Nigeria can break free from resource dependency and build a diversified economy, ensuring sustainable economic growth and environmental stewardship.

Keywords: Sustainable Nigeria, Economic Diversification, Agribusiness, Urbanisation, Climate Action

PHYTOCHEMICAL, BIOCHEMICAL AND ANTIMICROBIAL CHARACTERISTICS OF CINNAMON, CLOVE, CARDAMOM AND BLACK PEPPER

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ABSTRACT

Spices are most widely used culinary ingredients of Bangladesh along with many other countries of the world. This study shows the nutritional values, presence of many pharmacologically important phytochemicals and antimicrobial activities of four spices (cinnamon, clove, cardamom, and black pepper) used widely in the many types of food preparation of Bangladesh. Spices were collected from the local groceries of Sylhet city, Bangladesh. The proximate composition, total phenolic and flavonoid contents, presence of several phytochemicals, and antibacterial properties of the collected spices were all examined. The proximate analysis revealed the spices are excellent sources of many essential nutrients. The maximum amount of dry matter was present in cardamom (92.13%), ash and crude fiber in clove (8.77% and 14.29% respectively), crude protein in black pepper (10.97%) and ether extract in cinnamon (4.98%). The study also showed the presence of many pharmacologically active phytochemicals such as flavonoids, terpenoids, sterols, saponins and coumarins in various types of spice extracts. Quantitative analysis of the phenolic and flavonoid content demonstrated a great deal larger number of phenols (128.06 mg GAE/g spices) and flavonoids (45.75 mg QE/g spices) in clove. Clove along with cinnamon also showed to have significant antimicrobial potentials against *Salmonella typhimurium* and *Escherichia coli* with respect to the methods used for testing the antimicrobial activities, and again, clove showed the larger inhibition zones against the tested bacterial isolates. For that reason, these spices have the potential to treat illnesses brought on by *Salmonella typhimurium* and *Escherichia coli* instead of using antibiotics.

Keywords: Proximate, phenolic, flavonoid, antibacterial.

PLANT-MEDIATED GREEN SYNTHESIS OF SILVER NANOPARTICLES USING *COLEUS AMBOINICUS* (MEXICAN MINT) TO CONTROL MULTIDRUG RESISTANCE PATHOGEN OF POST-COVID PATIENT'S RESPIRATORY TRACT INFECTION: AN INTEGRATED EXPERIMENTAL, MOLECULAR DOCKING, AND MOLECULAR DYNAMICS SIMULATION STUDY

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ABSTRACT

Biosynthesis of AgNPs using *Coleus amboinicus* offers an eco-friendly approach with significant potential for biomedical applications due to their natural, non-toxic properties. *Coleus amboinicus* has proved to be a therapeutic agent for its medicinal properties. This study aimed to biosynthesise AgNPs from *Coleus amboinicus* extract to control antibiotic-resistant respiratory bacteria from post-COVID-19 patients and investigate potential natural inhibitors through in silico approaches. Three multidrug-resistant bacteria, including *Bordetella pertussis*, *Streptococcus pneumoniae*, and *Corynebacterium diphtheriae*, were isolated from post-COVID-19 patients and identified by 16S rRNA sequencing. Phytochemical analysis of *Coleus amboinicus* (Mexican mint) revealed 46 bioactive compounds. Green-synthesised silver nanoparticles from this leaf were characterised by UV–Vis, FTIR, DLS, XRD, and TEM, as well as assay cytotoxicity and antioxidant activity. The study isolated antibiotic-resistant respiratory pathogens, including *B. pertussis*, *S. pneumoniae*, and *C. diphtheriae*, and 16S rRNA sequencing revealed their virulence-associated receptors: (PtxA) pertussis toxin, (PLY) pneumolysin, and (DT) diphtheria toxin, respectively. Silver nanoparticle synthesis was confirmed by a colour change and UV–Vis peak at 434 nm. FTIR revealed alcohols, phenols, and alkenes as capping agents. DLS showed a mean size of 53.84 nm, while XRD and TEM confirmed spherical, face-centred cubic crystals. BSLA indicated low cytotoxicity (LC_{50} = 1475 µg/mL), and the DPPH assay showed 75% antioxidant activity. The AgNPs inhibited pathogens dose-dependently, with MIC values of 2 µg/mL against *B. pertussis*, *S. pneumoniae*, and *C. diphtheriae*. Further, molecular docking showed campesterol and 1-phenanthrenecarboxylic acid had strong binding to PtxA, PLY, and DT. ADMET analysis indicated no adverse effects, and 100 ns MD simulations confirmed their stability. These findings suggest that green-synthesized silver nanoparticles effectively inhibited these antibiotic-resistant respiratory pathogens in a dose-dependent manner. In the future, it could be a better, cheaper, and safer alternative to antibiotics.

Keyword: Silver nanoparticles, Covid-19, Respiratory tract infection, Antibiotic resistance.

A MICROSCOPIC ANALYSIS OF SHARED LANE CAPACITY UNDER VARIABLES GREEN TIME AND HETEROGENEOUS TURNING TRAFFIC MOVEMENTS.

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ABSTRACT

Optimizing the operational performance and capacity of urban intersections hinges on the efficient setting of signal timing parameters. This capacity is primarily governed by the green time allocation, the overall cycle length, and the complex composition of traffic flows. In the context of Algeria, the rapid expansion of car ownership coupled with a notable absence of locally adapted design guidelines presents significant hurdles for traffic engineers who often rely on uncalibrated international models. This study's key findings demonstrate that the enhancement of shared lane capacity through extended green time is subject to an optimal threshold, beyond which additional timing provides only marginal benefits. Crucially, the traffic composition, particularly the proportion of challenging left-turning vehicles, is found to exert a more potent influence on lane capacity than the signal timing parameters alone. These results underscore the urgent necessity of developing and implementing local signal control strategies tailored to specific traffic flow characteristics to ensure more efficient and sustainable intersection performance in the region.

Keywords: Turning movements; Shared lane capacity; Signal green time; Traffic composition; Algeria.

EFFECT OF RAINFALL ON SLOPE STABILITY USING FINITE ELEMENT METHOD (FEM): A CASE STUDY IN RANGAMATI, BANGLADESH

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ABSTRACT

Landslides triggered by intense rainfall regularly threaten lives and infrastructure in hilly regions such as Rangamati. This study analyzes a specific landslide event near Rangamati to evaluate how rainfall infiltration impacts slope stability. A numerical approach using the finite element method (FEM) was employed to simulate variations in rainfall intensity and duration, assessing their influence on the slope's factor of safety (FS). Initially, under dry conditions, the slope exhibited a relatively high FS; however, prolonged rainfall significantly reduced slope stability by increasing pore-water pressure and reducing soil shear strength. Simulation results revealed that after continuous rainfall, FS dropped below the critical value of 1.0, indicating imminent slope failure. This research underscores the necessity of integrating hydrological and geotechnical considerations into slope stability assessments, particularly in monsoon-affected areas. The successful application of FEM provides valuable insights for predicting rainfall-induced landslides and developing proactive strategies to mitigate their risks.

Keywords: Landslide Hazard**;** Slope Stability**;** Finite Element Method; Rainfall Infiltration; Factor of Safety.

COMPARATIVE WAVELET-BASED AND CONVENTIONAL FILTERING TECHNIQUES FOR SURFACE EMG ASSESSMENT IN LOW BACK PAIN PATIENTS

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ABSTRACT

Low back pain (LBP) is a common problem that affects daily life. This study compares statistical differences in surface electromyography (sEMG) signals between 15 healthy subjects and 10 LBP patients during the contraction phase of the Seated Side bend (SB) exercise. To process these signals, we used two methods e.g., conventional filtering (CF) and wavelet-based analysis with 'sym5' and 'db4' wavelets to derive time-domain and time-frequency domain features. Statistical analysis using t-tests revealed that wavelet-based filtering, especially with db4 and sym5, outperformed conventional methods in terms of noise suppression and feature extraction reliability. These findings indicate that wavelet-based sEMG signal analysis is more effective for differentiating muscle activity in LBP patients. The study had a small sample size, which should be improved in future research. Wavelet techniques show potential for improving clinical diagnosis and biomedical research in musculoskeletal disorders.

Keywords: Low Back Pain, sEMG, Signal Processing, Bandpass Filtering, DWT, Feature Extraction, Time-Frequency Domain.

GENETIC DIVERSITY AND POPULATION STRUCTURE OF CLIMBING PERCH (*Anabas testudineus*) COLLECTED FROM SOUTHEAST ASIA BASED ON MITOCHONDRIAL CYTOCHROME C GENE SEQUENCE ANALYSIS

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ABSTRACT

Anabas testudineus (climbing perch) is an ecologically and commercially important freshwater fish distributed across Asian countries. However, its population genetic structure in the Southeast Asian region remains poorly understood. This study conducted the genetic diversity and population structure of Bangladesh, Thailand, India, Indonesia, Philippines and Vietnam using mitochondrial cytochrome c oxidase subunit I (COI) gene sequences. A total of 81 sequences revealed a nucleotide composition biased regards AT (53.3%) with a deficiency of Guanine (G), suggesting consistent patterns in relation to other climbing perches. Overall, the rate of transition/transversion bias was 12, indicating the prevalence of transitions over transversions. High haplotype diversity (Hd = 0.82) coupled with low nucleotide diversity (π = 0.04) suggested significant haplotypic variation but relatively low divergence sequence, reflecting a recent population expansion or strong connectivity. The mean genetic distance among sequences was 0.05, within population diversity remarkably lower than between population divergence. Bayesian inference tree analysis revealed two well-supported clades, forming clusters of some intermixed populations. Haplotype network analysis identified 14 haplotypes, with Hap_6 being the most common, highlighting both diversity and complex evolutionary relationships. Population differentiation was overall high (F_{ST} = 0.70), with 11 pairwise differentiations being detected as moderate to high and significant among six distinct populations. These findings demonstrated that *A. testudineus* in six populations are genetically diverse and strongly structured. The results provide a valuable baseline information for the conservation, broodstock management and sustainable fisheries of *A. testudineus* in the Southeast Asian regions.

Keywords: *Anabas testudineus*, Genetic Diversity, Population Structure, COI, Southeast Asia.

MAGNETIC GRAPHENE OXIDE (MGO): THE BEST SOLUTION FOR REMOVING HEAVY METALS FROM WATER.

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ABSTRACT

Only 1% of the water on Earth is readily accessible for human consumption, with freshwater accounting for approximately 3% of the total. Unfortunately, urbanization, industrialization, and global evolution are also a threat to this finite supply of fresh water. In this study, we discussed the removal of heavy metal ions like Pb^{+2}, Cr^{+3}, Cu^{+2}, $Zn^{+2,}$ and Ni^{+2} from the water through the Magnetic Graphene Oxide (MGO) and indicated maximum removal efficiency with efficient reusability of drinking water. By fabricating the surface of graphene oxide (GO) with iron particles (Fe3+), a simple, quick, and easy technique was used to create magnetic graphene oxide (MGO). MGO was characterized using UV-VIS, FT-IR, SEM, XRD, and VSM. Efficient removal of toxic heavy metal ions from the water was studied using Atomic Absorption Spectroscopy (AAS). The adsorption performance of MGO was evaluated by examining the effects of various factors like pH, contact time, temperature, and adsorbent dose. The adsorption processes were spontaneous and endothermic, followed the Langmuir adsorption isotherm and pseudo-second-order kinetics model. The results exhibited that MGO is a competent adsorbent and disinfectant for safe drinking water.

Keywords: Water purification, Magnetic Graphene Oxide (MGO), Heavy metals, Atomic Absorption Spectroscopy (AAS).

COMPARATIVE EFFECTS OF CONVENTIONAL AND NO-TILLAGE SYSTEMS ON SOYBEAN PRODUCTIVITY AND SEED COMPOSITION UNDER MODERATE SALINITY

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ABSTRACT

Introduction: Soybean (Glycine max L.) is a vital oilseed and protein source but its productivity in Bangladesh's coastal areas is still low due to salinity in soil, and nutrient deficiency. Tillage practices directly affect soil aeration, water infiltration, and nutrient cycling, which in turn influence crop performance and seed quality. Methods: A two-factor factorial field experiment was carried out using two tillage systems; conventional tillage and no-tillage; and two soybean varieties, Bangladesh Soybean-4 (BD-4) and BARI Soybean-6. A randomized complete block design with six replications was followed with standard agronomic management where plant growth, yield components, and seed nutritional composition were analyzed. Results: Both tillage and variety had strong effects on soybean performance. In case of conventional tillage, plant height, branching, chlorophyll content, and pod formation shown better improvement compared with no-tillage. Conventional tillage produces 43% greater seed yield than under no-tillage treatment. BARI Soybean-6 shown best outcome, particularly under conventional tillage. Nutritionally, seeds from this treatment hold 8% higher crude protein; better ether extract, and gross energy is also statistically higher than no tillage treatment. Positive relationships among chlorophyll content, seed yield, and biological yield confirmed that improved photosynthetic activity contributed directly to higher productivity. Conventional tillage had superior yield and grain quality other than no tillage which can turn it in a prospect. Conclusion: Conventional tillage significantly enhanced soybean growth, yield, and seed quality in saline coastal soils specially for BARI Soybean-6.

Keywords: soybean, tillage systems, coastal area, nutritional quality, saline soil

DESIGN OF NON-ADAPTIVE FILTERING AND WAVELET TRANSFORM TECHNIQUES FOR EMG NOISE REDUCTION

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ABSTRACT
Electromyography (EMG) is an important tool for assessing neuromuscular activity; however, its diagnostic and analytical utility is often hindered by noise contamination, including motion artifacts, power line interference (PLI), and baseline drift. This study proposes and evaluates two advanced EMG denoising strategies: (i) Discrete Wavelet Transform (DWT) integrated with a bandpass filter and (ii) a non-adaptive filtering method involving an IIR notch filter combined with a bandpass filter. Twenty healthy participants were taken for EMG data collection from the medial head of the gastrocnemius muscle. The performed movements include dorsiflexion and plantarflexion. Raw EMG data was denoised using both denoising technique and noise mitigation efficiency was assessed using quantitative measures, including Signal-to-Noise Ratio (SNR), Slope Sign Change (SSC), Root Mean Square (RMS), and Zero Crossing (ZC). Statistical validation using a t-test disclosed that both approaches significantly strengthen EMG signal quality ($p<0.05$), where DWT-based technique attaining superiority in decreasing noise while retaining physiological aspects intact. These findings highlight the capability of wavelet-based filtering as a robust method for EMG denoising, offering potential to improve the accuracy of EMG-based clinical diagnostics, rehabilitation monitoring, and human–machine interface applications.
Keywords: EMG, Foot Movement, IIR Notch Filter, DWT, Feature Extraction, Statically Analysis, p-test.

E-WASTE GENERATION AND DISPOSAL PRACTICES IN URBAN BANGLADESH: A CASE STUDY OF KUSHTIA MUNICIPALITY

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ABSTRACT

Electronic waste (e-waste) is rapidly emerging as a critical challenge within urban waste management systems in Bangladesh, owing to escalating electronic consumption, shortened device life cycles, and the absence of institutionalized recycling mechanisms. The study examines consumer awareness, behavioral practices, disposal patterns, and institutional limitations associated with e-waste management in Kushtia Municipality. The study employed a structured questionnaire survey, selecting 5 key administrative staff through purposive sampling, while 52 consumers and 18 electronic retailers were selected through random sampling from the municipal area, resulting in a total sample size of 75 participants. Findings reveal marked gaps in public knowledge, with only 55.8% of respondents familiar with the term ‘e-waste’, 25% aware of appropriate disposal methods, and merely 5.8% recognizing the need for specialized treatment. High ownership and frequent replacement of electronic devices, driven by technological obsolescence (42.9%) and malfunctioning (29.9%), substantially contribute to e-waste generation. Disposal remains largely informal, dominated by selling discarded items to unregulated scrappers (60-76%) or storing them at home, while environmentally unsafe practices such as dumping and burning persist. Furthermore, the complete absence of formal collection points and recycling staff, alongside widespread dissatisfaction with municipal waste services, highlights significant structural deficiencies. The

significance of this study lies in its contribution to understanding the behavioral and systemic factors underpinning e-waste mismanagement, offering evidence essential for developing integrated waste management strategies, strengthening regulatory frameworks, and designing targeted awareness interventions. By identifying critical gaps, the study provides actionable insights to support the transition toward a more sustainable and accountable urban waste management system.

Keywords: E- waste, Urban waste management, Consumer behavior, Recycling and disposal practices, Institutional limitations

SIMULATION-BASED EVALUATION OF METHANOL-DIESEL BLENDS IN CI ENGINES USING ANSYS: PERFORMANCE AND EMISSION INSIGHTS

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ABSTRACT

This study presents a comprehensive simulation-based investigation into the viability of methanol as a supplementary fuel in compression ignition (CI) engines, conducted using ANSYS Forte. The results indicate a modest improvement in brake thermal efficiency and brake specific energy consumption (BSEC), attributed to enhanced combustion in fuel-rich zones and reduced in-cylinder heat losses due to methanol's lower flame temperature. While a slight increase in brake specific fuel consumption (BSFC) is observed—owing to methanol's lower energy density—the trade-off is offset by significant environmental benefits. Notably, methanol-diesel blends demonstrate a 15.96% reduction in NO_x emissions, a 3.39% decrease in CO_2, and substantial declines in particulate matter (PM) and smoke emissions by 51.37% and 44.13%, respectively. These improvements are linked to more complete combustion and effective oxidation of soot precursors. Validation of the simulation results was achieved through comparison with prior studies by Iliev et al. (2020), affirming the model's reliability. Future work will focus on experimental validation to further substantiate these findings and explore practical implementation pathways.

Keywords: Simulation using ANSYS, Methanol-Diesel, CI Engines.

AI FOR QR CODE SAFETY

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ABSTRACT

With the rapid adoption of QR codes in payments, authentication, and information sharing, security risks have also escalated. Malicious actors increasingly exploit QR codes by embedding harmful links that redirect users to phishing websites, malware downloads, or fraudulent portals. Users often trust and scan QR codes without verifying the underlying content, making them vulnerable to cyberattacks. To address this issue, this project proposes an AI-based QR Code Safety System that analyzes embedded links for potential threats before allowing access. The system first extracts the URL from the scanned QR code and subjects it to multiple layers of security checks. Using machine learning and natural language processing, the AI model evaluates the domain reputation, URL structure, and contextual patterns associated with phishing or scam sites. Additionally, it integrates threat intelligence databases and malware blacklists to detect known malicious sources. Suspicious or unsafe links are flagged and blocked, while safe links are allowed to open seamlessly. This solution aims to enhance user confidence by providing real-time QR code verification without disrupting convenience. The project contributes to safer digital transactions, secure information sharing, and effective defense against phishing attacks, making it a valuable tool for individuals, businesses, and financial institutions.

Keywords: AI-Based QR Code Safety System, QR Code Security, Phishing Detection, URL Analysis, Machine Learning, Natural Language Processing (NLP), Cybersecurity, Threat Intelligence, Domain Reputation, Malware Detection, URL Structure Analysis, Safe Browsing, Real-Time Verification, Secure Transactions, Fraud Prevention, Digital Safety, Data Protection, AI Threat Detection.

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DEVELOPMENT OF A MODULAR COVERT AUDIO-VIDEO SURVEILLANCE SYSTEM FOR NATIONAL SECURITY APPLICATIONS USING 4G/5G TRANSMISSION

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ABSTRACT

This paper presents the ongoing development of an innovative modular hardware-software system designed for the discreet implementation of authorized technical surveillance measures under national security warrants, within the framework of the Romanian SOL2024-T6 project funded by UEFISCDI and coordinated with the Ministry of Internal Affairs (MAI) of Romania. The system addresses the need for reliable, long-term covert audio-video monitoring in challenging environments (distances ≈2 m, harsh installation conditions, limited accessibility, no requirement for court-admissible evidence). Key hardware features include a compact single-board computer platform with support for analog (RCA) and optional Full-HD digital cameras, wired microphones (with best-effort exploration of wireless alternatives), a 4G/5G cellular modem for encrypted live streaming, flexible power supply (230 V AC mains, 12 V DC vehicle, 5 V auxiliary with optional power-bank backup), surge immunity, passive cooling, and remote health monitoring (input voltage, temperature, signal strength). Automatic graceful degradation mechanisms (resolution/framerate reduction, fallback to 4G or audio-only mode) ensure operational continuity under adverse conditions, while a hardware watchdog provides reliable restart capability. The software architecture enables continuous encrypted transmission of the audio-video stream to a remote server without local storage, automatic segmentation into ≈30-minute files with descriptive naming, on-demand playback, and real-time watermarking (camera identifier + timestamp). Feasibility studies are underway for audio extraction from video streams and speech-to-text transcription. The first functional prototype based on Raspberry Pi 5, an analog camera, and a 4G modem has been successfully demonstrated in May 2025, validating end-to-end live capture, transmission, reception, and segmented storage. Subsequent iterations focus on replacing active cooling with fully passive solutions, optimizing power consumption, and finalizing lightweight encryption/APN-private communication schemes. The resulting system offers a cost-effective, rapidly deployable, and resilient platform for authorized national-security surveillance operations, with potential extensions to other law-enforcement and intelligence scenarios.

Keywords: Covert surveillance, audio-video streaming, 4G/5G transmission

TRANSFORMING DAIRY WHEY BYPRODUCTS INTO A NUTRITIOUS MANGO-INFUSED FUNCTIONAL BEVERAGE: FORMULATION, NUTRITIONAL VALUE, AND SENSORY ACCEPTANCE

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ABSTRACT

This study aimed to develop and characterize a functional whey-based beverage, utilizing whey -a nutrient-rich byproduct of the dairy industry-and mango pulp to create a refreshing drink that minimizes milk wastage and provides added nutritional value. Lemon was incorporated for enhanced flavor, while castor sugar was used as a natural sweetener, with no artificial additives. Three beverage formulations varying in whey and mango content were prepared and evaluated for physical, chemical, biological, and sensory properties using standard AOAC methodologies. The produced beverage exhibited a vibrant yellow-orange color, smooth mouthfeel, and stable consistency due to the inclusion of mango pulp, nata de coco, and xanthan gum. Analytical results demonstrated that the beverage is a good source of protein, minerals (such as calcium,

potassium, phosphorus, and magnesium), and dietary fiber, with pH between 3.5-4.5 ensuring microbial safety and shelf-life stability. Sensory analysis by a trained panel indicated that consumer acceptability of the beverage was high across all tested attributes - including color, aroma, viscosity, sweetness, and overall acceptance - with the most balanced formulation containing intermediate ratios of whey and mango pulp. The findings establish that the developed whey-mango drink is not only a sustainable solution for whey utilization but also a nutritious, stable, and organoleptically pleasing functional beverage suitable for health-conscious consumers.

Keywords: whey utilization, functional beverage, mango drink, sustainability, sensory quality

DEVELOPMENT AND CHARACTERIZATION OF BIOACTIVE AND SMART BIOFILMS BASED ON PLANT EXTRACTS AND OILS FOR SUSTAINABLE MATERIAL APPLICATIONS

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ABSTRACT

The creation of multifunctional biodegradable films with colorimetric, antibacterial, and antioxidant qualities is shown in this work as sustainable materials for active packaging. The anthocyanin fraction of *Hibiscus sabdariffa*, the fatty oil of *Opuntia ficus-indica*, and the essential oil of *Salvia officinalis* were plant-derived extracts that were added to the natural polymers xanthan and chitosan used to build the biofilms. While GC-MS verified the presence of key fatty acids, including linoleic and palmitic acids and terpenoids like α-caryophyllene and β-caryophyllene, phytochemical investigations using HPLC-DAD revealed significant phenolic compounds, primarily 3-hydroxytyrosol, vanillic acid, and 4-hydroxybenzoic acid. While UV-Vis measurements showed effective light-barrier efficacy and reversible colour changes associated with anthocyanin reactivity, FTIR spectra revealed strong molecular interactions

within the biopolymer matrix. With MBC/MFC values below 250 µg/mL against tested bacteria, the films demonstrated strong antimicrobial action and good antioxidant capacity. Their environmental compatibility was confirmed by biodegradability tests, which showed a quick and thorough breakdown. Anthocyanin-based films colorimetric transition under varying pH and storage conditions demonstrated their potential as intelligent freshness indicators. This collaborative project advances the development of renewable active materials for smart packaging technologies by combining phytochemical profiling, materials engineering, and sustainable design to create repeatable, environmentally friendly biofilms with dual functional and aesthetic roles.

Keywords: Degradable biofilms; Xanthan; Chitosan; Plant extracts; Antioxidant effects; Antimicrobial properties.

GUARDNEX - ADVANCED MULTILINGUAL SPAM DETECTION PLATFORM

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ABSTRACT

Spam attacks are constantly changing on digital communication platforms. They often use multiple languages and channels to get around traditional filtering systems. This paper presents GuardNex, a system that detects spam across multiple channels and languages. It can identify spam in English, Spanish, and Bangla in text messages, emails, and WhatsApp communications. GuardNex uses a simple but effective machine learning workflow. It first applies TF-IDF to turn text into meaningful numerical features and then uses a Naive Bayes classifier to make predictions. This model is selected because it runs fast, scales well with large datasets and performs reliably with text that has many features. To ensure realistic performance the system is trained and evaluated on multilingual datasets that include different writing styles, informal language and message patterns from various communication platforms. Experimental results indicate that GuardNex achieves about 92% accuracy. It performs as well as or better than similar systems mentioned in existing studies. The results show that lightweight models paired with optimized preprocessing and multilingual representation can effectively detect spam across various communication channels. GuardNex provides a practical and flexible framework for organizations that need dependable and language-inclusive spam protection.

Keywords: Machine Learning, GuardNex, Naive Bayes, NLP, TF-IDF, Attack

STRUCTURAL AND OPTICAL CHARACTERIZATION OF CBD DEPOSITED COPPER SULPHIDE THIN Films

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ABSTRACT

In recent years thin films (TF) technology has shown remarkable progress in the discovery of new materials including nano and bio based materials, magnetic materials, etc. [1]. Among them, semiconductor TF are particularly significant due to their electrical and optical properties, which make them essential in modern optoelectronic device applications[2].The prime goal of the present research is to investigate the effect of deposition time (DT) on the structural and optical properties of copper sulfide thin films (CSTF). DT dependent CSTF were synthesized onto glass substrates via the chemical bath deposition (CBD) method. X-ray diffraction (XRD) analysis confirmed the CSTF are polycrystalline in nature with hexagonal structure. From FTIR spectra it is noticed that the absorption peaks at 580 cm^{-1} is assigned to Cu–S stretching vibration, confirming the formation of CSTF. The UV-Vis spectroscopic analysis revealed that the absorbance increased with longer DT in the UV region while it decreased with increasing wavelength in the visible region. The maximum absorbance was observed for 100 min deposited CSTF. Transmittance, *T%* inversely correlated with absorbance. Moreover, the refractive index enriched with DT, attaining a maximum of approximately 2.2. The band gap energy values were found within the range 2.66-2.09 eV for CSTF at diverse DT. Urbach energy declined from 3.41 to 1.93 eV with higher DT. Additionally, the alteration of other optical parameters due to DT, such as extinction coefficient, absorption coefficient, skin depth, real dielectric constant, steepness parameter, etc., was also discussed for these CSTF.

Figure:

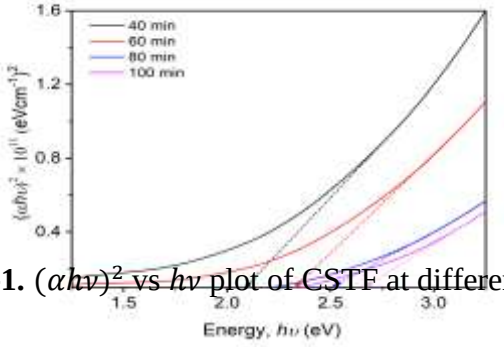

Fig-1. $(\alpha h\nu)^2$ vs $h\nu$ plot of CSTF at different DT.

EVALUATION OF THE PHYTOCHEMICAL PROFILE AND ANTIOXIDANT ACTIVITY OF *STEVIA REBAUDIANA* BERTONI

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ABSTRACT
Plants rich in bioactive compounds have the potential for widespread use in food, cosmetics, pharmaceuticals, and phytotherapeutics thanks to their bioactive compounds. Among these plants, *Stevia rebaudiana* Bertoni stands out for its natural sweetening properties and rich phytochemical content. Its leaves contain steviol glycosides, which are 100–300 times sweeter than sucrose, and are also rich in flavonoids and phenolic compounds. These compounds prevent cellular damage caused by oxidative stress by neutralizing free radicals and offer a protective effect against degenerative diseases. In this study, the bioactive compound profile and antioxidant capacity of the extract obtained from *Stevia rebaudiana* Bertoni leaves were evaluated. Extraction was carried out using an ultrasonic probe-assisted homogenizer to maximize the extraction of active compounds. The antioxidant activity of the obtained extract was determined using the Trolox Equivalent Antioxidant Capacity (TEAC) method based on the ABTS (2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)) radical cation, and a new HPLC-DAD method was developed and validated for the simultaneous determination of protocatechuic acid, catechin, gentisic acid, polydatin, p-coumaric acid, coumarin, resveratrol, quercetin, and rebaudioside A. The method showed high linearity ($R^2 = 1$), and the LOD and LOQ values of the compounds were found to be 0.02–19.25 ng/mL and 0.08–64.17 ng/mL, respectively. The compound detected at the highest concentration was rebaudioside A (345.808 µg/mg), followed by resveratrol (4.684 µg/mg), p-coumaric acid (0.341 µg/mg), and polydatin (0.219 µg/mg). The IC_{50} value of *Stevia rebaudiana* Bertoni was determined as 1589.688 mg/mL according to the ABTS method. In conclusion, the combined application of the developed and validated HPLC-DAD method and ABTS analysis enabled a comprehensive evaluation of the bioactive compound profile and antioxidant capacity of *Stevia rebaudiana* Bertoni. The obtained findings demonstrate that this plant is not only a natural sweetener but also a phytochemically valuable potential source of functional food and health-supporting ingredients.

Keywords: *Stevia rebaudiana* Bertoni, Steviol glycosides, Phenolic compounds, Antioxidant activity, HPLC-DAD.

MECHANISMS OF MASS GENERATION FOR NEUTRINOS IN SU(5) GRAND UNIFIED THEORIES

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ABSTRACT

With the discovery of neutrino oscillations it has become certain that at least two of the three neutrinos must be massive, albeit with masses 8.7×10^{-3} and 5.0×10^{-2} eV in normal ordering or 4.9×10^{-2} eV for both in inverted ordering much smaller compared to the other matter fields of the Standard Model. The precise nature of the mass is still elusive, though, that is, whether neutrinos are Majorana or Dirac. The simplest, although not predictive, possibility in non-supersymmetric SU(5) grand unified theories corresponds to adding at least two right-handed singlets, $\mathbf{1}_F$, which results in Dirac neutrinos. There are only three other mechanisms of mass generation at tree level and they all lead to Majorana neutrinos. In the first two Standard Model matter fields are extended by two fermionic representations that comprise either a Standard Model singlet or a weak triplet multiplet. These are dubbed Type-I and Type-III seesaw, respectively. As the name implies, these two mechanisms tie the smallness of the neutrino mass to the large mass of the hypothetical fermions which is roughly of order $10^{13} - 10^{15}$ GeV. The adjoint, i.e., $\mathbf{24}_F$, and $\mathbf{75}_F$ are the smallest representations that are appropriate for this purpose. The last mechanism called Type-II seesaw augments the Standard Model particle content by weak triplet scalars. $\mathbf{15}_S$ contains precisely such a multiplet. These are not the only possibilities though, as the neutrino masses could owe their smallness to their radiative origin. In this case, the numerical factors that appear in a loop calculation lead to a small mass for the neutrino. This can be accomplished through the use of a $\mathbf{10}_S$ as was demonstrated recently.

Keywords: Beyond Standard Model, Grand Unified Theories, Neutrino Oscillations

SYNTHESIS, CHARACTERIZATION, AND ANTIMICROBIAL PHOTODYNAMIC ACTIVITY OF PORPHYRIN–INDAZOLE HYBRIDS

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ABSTRACT

In this work, novel *porphyrin–indazole hybrid* compounds were synthesized via a Knoevenagel condensation between meso-substituted porphyrin aldehydes and N-substituted nitro-indazolyl acetonitriles [1]. The resulting conjugates were isolated in moderate to good yields (≈ 30–60 %) and fully characterized by a combination of spectroscopic methods (^{1}H NMR, UV–Vis, mass spectrometry) and photophysical studies. Upon visible-light irradiation, these hybrids demonstrated efficient generation of singlet oxygen ($^1O_2$), confirming their capacity as photosensitizers [2]. Their antimicrobial photodynamic therapy (aPDT) performance was evaluated in vitro against *Staphylococcus aureus*, including methicillin-resistant strains (MRSA). The porphyrin–indazole hybrids showed a significant photoinactivation effect, which was further potentiated by the addition of potassium iodide (KI), suggesting a synergistic enhancement of reactive iodine species. One of the most promising derivatives achieved a substantial log-reduction in bacterial viability under light exposure, with minimal dark toxicity. These results highlight the potential of porphyrin–indazole conjugates as effective photosensitizers for antimicrobial applications, especially in the context of resistant bacterial strains [3].

Keywords: Porphyrin-indazole hybrids, Antimicrobial photodynamic therapy (aPDT), Singlet oxygen generation, MRSA (*Staphylococcus aureus*), Potassium iodide (KI), Photosensitizer

OYSTER MUSHROOMS: THERAPEUTIC SIGNIFICANCE IN CVD

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ABSTRACT
Mushrooms especially the Pleurotus species have a significant nutritional and medicinal properties reason for their gained attention. Being nutritionally rich as in proteins, vitamins (B-complex, C and D), fiber and bioactive compounds like polysaccharides, lipids, triterpenoids and lectins that contribute their role as antimicrobial, antioxidant and cholesterol-lowering effects. They have been studied extensively for their potential role as cardiovascular health regulator, particularly in lowering the cholesterol levels and mitigating the risks of cardiovascular disease. Due to the presence of β-glucans and lovastanin these has been linked to lipid regulation, anti-inflammatory and immune system enhancement, making them a successful nutraceuticals. Along with these their cultivation on different agricultural waste substrates presents them as environmentally sustainable approach. This review focuses on the nutritional composition, therapeutic applications and cultivation methods of oyster mushrooms emphasizing their ability as functional food in prevention of cardiovascular diseases and overall human health improvement.
Keywords: Oyster mushrooms, Pleurotus species, Cardiovascular diseases, β-glucans, Lovastatin, Functional foods, Nutraceuticals

MACHINE LEARNING APPROACHES FOR PREDICTING QUANTUM STATES IN SIMPLE QUANTUM SYSTEMS

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ABSTRACT

Machine learning (ML) has rapidly emerged as a transformative tool for predicting quantum states in simple quantum systems, addressing key challenges in quantum information science. Traditional quantum state characterization methods, such as full quantum state tomography, are resource-intensive and scale poorly with system size. Recent advances demonstrate that ML approaches—including neural networks, regression models, and hybrid quantum-classical algorithms—can efficiently reconstruct, classify, and predict properties of quantum states using limited or incomplete measurement data. Neural networks have been successfully trained to classify quantum states, estimate fidelity, and identify entanglement, often requiring significantly fewer measurements than conventional techniques. Deep autoregressive models and quantum convolutional neural networks further enhance the expressive power and scalability of these methods, enabling accurate simulation and recognition of many-body quantum states. Additionally, ML-assisted Bayesian estimation and dimension-adaptive learning frameworks offer robust solutions for state reconstruction and system identification, even when the system's dimensionality is not precisely known. Physics-informed neural networks and regression on quantum computers have also shown promise in predicting ground state energies and other continuous properties with high accuracy. Collectively, these developments highlight the potential of machine learning to accelerate quantum state prediction, reduce experimental overhead, and provide new insights into the structure and dynamics of quantum systems. This abstract reviews the state-of-the-art ML methodologies for quantum state prediction, discusses their advantages over traditional approaches, and outlines future directions for integrating machine learning into quantum technologies and experimental protocols.

Keywords: Machine learning, quantum states, neural networks, Schrödinger equation, energy levels, computational physics

IMPACT OF THE HUBBARD U PARAMETER ON THE OPTOELECTRONIC RESPONSE OF ANATASE TiO_2 WITHIN DFT+U CALCULATIONS.

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ABSTRACT

Anatase TiO_2 is an oxide that has been extensively studied due to its importance in photocatalysis and optoelectronic devices. In order to shed light on its structural and electronic behavior, calculations based on fundamental principles were performed using the CASTEP code within the plane wave pseudopotential framework. The Perdew-Burke-Ernzerhof form of the generalized gradient approximation was applied, along with ultrasoft pseudopotentials. As GGA generally underestimates the band gaps in correlated systems, a Hubbard correction was introduced to improve the description of the 3d states of titanium. The Hubbard parameter U was adjusted between 0 and 13 eV in order to reproduce the experimental electronic band gap. The calculated band gap increased steadily up to U = 10 eV before decreasing at higher values. The closest match to the reported experimental band gap of 3.2 eV was obtained at U = 9 eV, for which the calculated band gap reached 3.198 eV.

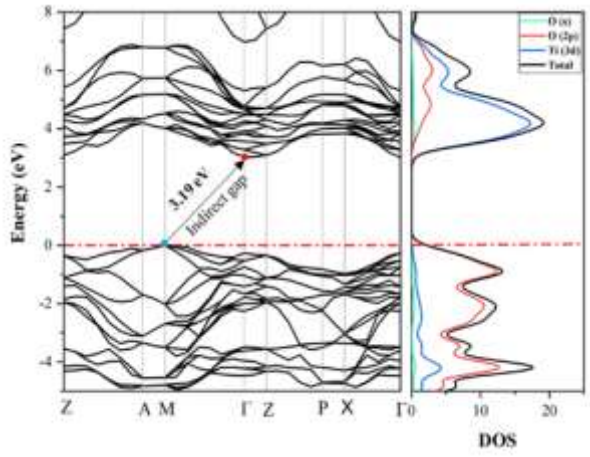

Fig. Band structure and DOS of anatase TiO_2

The Geometric optimization engendered lattice constants a = b = 3.776 Å and c = 9.486 Å, with deviations of less than 1% from experimental values. In addition, the optimized Ti–O apical bond-length ratio (u = dap/c) aligned well with earlier theoretical and experimental studies, confirming the reliability of the computational setup. The electronic band structure indicated an indirect bandgap, consistent with the arrangement of states in anatase. Furthermore, the density of states made it clear that the valence band was dominated by O 2p orbitals, while the conduction band was mainly formed by Ti 3d states.

These findings show that the structure and optoelectronic response of anatase TiO_2 could be accurately described using a calibrated GGA+U method. The improved U parameter offers precise predictions and provides a strong foundation for additional computational research on photocatalysis and advanced optoelectronic applications.

Keywords: Anatase TiO_2, Electronic structure, Bandgap energy, Hubbard parameter, DFT+U

IN SILICO DESIGN OF NOVEL DIHYDROPTERIDONE DERIVATIVES WITH OXADIAZOLES AS POTENT INHIBITORS OF MCF-7 BREAST CANCER CELLS

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ABSTRACT

Pharmaceutical treatment protocols or combination therapies based on chemical compounds make it possible to target cancer cells, which can be complicated by several factors, including their resistance to bioactive compounds and the potential for drugs to damage certain healthy cells. This project was designed to assess the structural relationship between new dihydropteridone-derived compounds bearing an oxadiazole moiety and their corresponding cytotoxicity against breast cancer, using computational chemistry tools. The aim of this research is to better understand how compound properties influence their activity and to understand the underlying mechanisms, which could then be integrated into the anticancer drug design process with a view to recommending new optimized compounds likely to have the desired activity. The results show that the predicted molecules possess enhanced selective cytotoxic inhibitory activity against breast cancer cells (MCF-7). Guided by these analyses, we designed five novel dihydropteridone derivatives incorporating an oxadiazole moiety. These compounds exhibited favorable interactions with key breast cancer-related proteins, demonstrated enhanced dynamic stability within their binding sites, and adhered to established drug-likeness principles. Importantly, these compounds displayed promising oral absorption (88%) in preliminary assessments and exhibited no significant toxicity. These findings suggest that these novel dihydropteridone-oxadiazole derivatives warrant further investigation as potential multifunctional agents for the treatment of breast cancer cells (MCF-7).

Keywords: QSAR, novel dihydropteridone derivatives, Molecular docking, oxadiazole, Molecular dynamics, ADMET propriety, MCF-7, Breast cancer cells.

GEOSPATIAL MODELING OF URBAN FLOOD VULNERABILITY IN DHAKA CITY: AN INTEGRATED REMOTE SENSING, GIS, AND AHP-FUZZY SMCE APPROACH

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ABSTRACT

The severity of floods has increased in recent years, especially in urban areas, and they pose significant threats to infrastructure, human life, and the environment. Increased urbanization, destruction of forests, and climate change are the main causes of these escalated situations, highlighting the necessity of appropriate disaster risk reduction measures. To address these issues, this study integrates the Analytic Hierarchy Process (AHP), Fuzzy Logic Model, Spatial Multi-Criteria Evaluation (SMCE) Method, and Geoinformation Technology to provide an enhanced methodological approach for flood vulnerability assessment in Dhaka, Bangladesh. Integrating these approaches provides a systematic and thorough framework for evaluating flood vulnerability by incorporating spatial analysis, uncertainty modeling, and decision-making procedures. To identify high-risk flood-prone areas, Geographic Information Systems (GIS) are essential to this study because it makes it easier to integrate, analyze, and visualize spatial data layers. The AHP method ensures a methodical and quantitative approach to decision-making by determining the relative importance of fifteen specified flood susceptibility factors. The Fuzzy Logic Model uses fuzzy linear membership functions to convert the input variables into fuzzy sets, which tackles the inherent ambiguity and uncertainty related to flood vulnerability. The flood vulnerability assessment becomes more accurate by this fuzzification process. After that, a thorough flood vulnerability map is created using the weighted sum overlay technique, which captures regional variations in risk levels. According to the study's findings, about 9%, 21%, and 29% of the entire study area are classified as being in extremely high, high, and moderate vulnerability zones, respectively. This suggests that almost 60% of Dhaka is at high risk of flooding. Kamrangirchar and Khilgaon have been selected as the most vulnerable regions due to the presence of highly high-vulnerability areas throughout their areas. The study utilizes an accuracy assessment and computes the overall accuracy, user accuracy, producer accuracy and kappa coefficient value to verify the model's reliability, and it achieved an overall accuracy score for reliability of 88%. This validation demonstrates an excellent level of accuracy in evaluating flood vulnerability, confirming the robustness of the combined approach. Based on the findings, a strategic management plan has been developed to address the flooding threats in the area. Given that the modeling approach integrates remote sensing data, GIS, and AHP-Fuzzy SMCE techniques, it has the potential to be adapted for use in other urban areas, both within the country and internationally, with some localized adjustments. Stakeholders and government officials can reduce the risk of flooding and improve urban resilience by utilizing the synergies of AHP, Fuzzy Logic, SMCE, and GIS. This strategy's multidisciplinary nature highlights its potential for tackling intricate flood threats and promoting long-term disaster risk reduction projects.

Keywords: Urban flooding · Analytical hierarchy process (AHP), Fuzzy membership function · Geographic information system (GIS) & Remote sensing

CLIMATE CHANGE AND ANTHROPOGENIC WATERLOGGING: SMALL FARMERS' VULNERABILITY TO FOOD SECURITY IN BARIND AREA OF BANGLADESH

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ABSTRACT

The Barind region of Bangladesh is increasingly affected by the combined impacts of climate change and human-induced water management challenges, which significantly threaten agricultural livelihoods and food security. Smallholder farmers in this drought-prone area have experienced rising temperatures, erratic rainfall, and prolonged dry spells, which disrupt traditional cropping patterns. At the same time, poorly planned infrastructure—such as blocked culverts, roads, and drainage near settlements and institutional areas—prevents natural water flow, causing localized waterlogging even after moderate rainfall. This dual pressure of climatic stress and anthropogenic waterlogging disrupts crop establishment, delays planting, increases production costs, and reduces yields of key crops. The aim of this study is to assess how climate variability and anthropogenic waterlogging interact to heighten vulnerability among small farmers. Data were collected through household surveys, focus group discussions, and field observations across selected Barind villages. Findings show that these combined pressures reduce crop yields, delay planting, and increase food insecurity. Limited adaptive capacity – due to low income, weak institutional support, and restricted access to climate-smart technologies – further intensifies food insecurity risks. Strengthening water management system, improving drainage infrastructure, and promoting adaptation strategies are essential to reduce vulnerability, enhance resilience and secure food production in the Barind region.

Keywords: Climate change, anthropogenic waterlogging, small farmers, food security, agriculture, Barind region, Bangladesh.

UTILIZATION OF OLIVE MILL SOLID WASTE-BASED ACTIVATED CARBON FOR THE EFFECTIVE ELIMINATION OF PHENOLIC COMPOUNDS IN OLIVE-MILL WASTEWATER: A STUDY ON OPTIMIZATION, KINETICS, AND ISOTHERMS

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ABSTRACT

Olive mill wastewater (OMW) poses a significant environmental challenge due to its high organic and phenolic content. This study explored the use of activated carbon (AC) derived from olive mill solid waste (OMS) as an adsorbent for removing phenolic compounds (PCs) from OMW. The preparation of AC was optimized using response surface methodology (RSM), focusing on activating agents (KOH, $ZnCl_2$, and H_3PO_4), activation temperatures (600–800°C), and impregnation ratios (2–4). Results revealed that $ZnCl_2$ was the most effective activating agent, producing the highest iodine number of AC. The optimal conditions for $ZnCl_2$-activated carbon (ACZ) were achieved at 700°C with a 4:1 impregnation ratio. The ACZ and raw OMS were characterized using TG/DTG, ATR-FTIR, SEM, and XRD analyses. Batch adsorption experiments were conducted to assess the removal of PCs from OMW, examining factors such as pH, contact time, adsorbent dose, initial polyphenol concentration, and temperature. The adsorption data aligned well with the Langmuir isotherm model ($R^2 = 0.990$) and the pseudo-second-order kinetic model ($R^2 = 0.990$), suggesting chemisorption as the primary mechanism. Desorption studies using hydrochloric acid (HCl) recovered 68% of adsorbed PCs in the first cycle and 20% in the second cycle.

Keywords: Pyrolysis; Response surface methodology; Polyphenols; Adsorption; Desorption

FULL TEXT

AN APPROACH ON THE DISTRIBUTED LOAD DEFLECTION OF A DEFINED MATERIAL BY USING HERMITE POLYNOMIALS

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ABSTRACT

This study provides an attempt to analyze the behaviors of materials in structures when the material deflection is chosen as Gaussian-type functions. By taking the Gaussian-type material deflection into account, the related parameters that occur accordingly have been expressed in terms of the Hermite polynomials. Particularly, by using the Rodrigues' type formula, it has been indicated that there exist relationships of the Hermite polynomials with the governing differential equations of materials. Overall, this study reveals the usability of the Rodrigues' type formula of the Hermite polynomials and other special polynomials for mathematically modeling the deflection on materials.

Keywords: Computational analysis, Deflection of Materials, Gaussian function, Hermite polynomials, Structural member.

1 Introduction, Definitions and Preliminaries

Materials are used to manufacture beams which can be briefly defined as horizontal structural elements carrying vertical loads in civil engineering. Different deflections on these types of materials that one may encounter in the application need to be modeled in some way. In this context, the effects of the load imposed on the materials by selecting the deflection of the materials as different kind of functions have been investigated for years by some researchers, and formulas have been developed for these effects; for examples (among others), see (Alderliesten 2018, Alderliesten 2025, Kocatürk et al. 2010, Shukur et al 2023, Tuan Ya et al. 2019); and also see the references cited therein.

As for the main purpose of the present study, it is two-fold: First is to provide an attempt to analyze how the materials behave when their deflection is chosen as Gaussian-type functions. Second is to investigate the relationships of the material-governing equations with the Hermite polynomials.

Below, we begin by recalling the notations and definitions necessary to achieve the main aim of this study.

Let E, I, w and q denote the modulus of elasticity, the moment of inertia (or second moment) of a plane area, the deflection of the material (in the z direction at some position x) and the intensity of distributed load (force per unit length), respectively. Then, the Euler–Bernoulli equation is given by

$$\frac{d^2}{dx^2}\left(EI\frac{d^2w}{dx^2}\right) = q,$$

which describes the relationship between the functions w and q for the case when the product EI (known as the flexural rigidity) differ depending on the values of x (Gere and Timoshenko 1997).

Let V, M and θ denote the shear force, the bending moment and the slope in the material. Then, in the case when the flexural rigidity EI is a constant with the intensity of distributed load q applied downwards, the material-governing equations are given by the following differential equations (Gere and Goodno 2008):

$$EI\frac{dw}{dx} = \theta,$$

$$EI\frac{d^2w}{dx^2} = M,$$

$$EI\frac{d^3w}{dx^3} = V$$

and

$$EI\frac{d^4w}{dx^4} = q.$$

Note that in the above equations, the sign of the distributed load is not considered since it is assumed that the load is applied downwards.

As for the Hermite polynomials, they constitute a sequence of orthogonal polynomials possessing a remarkable role in a wide range of fields from mathematics to engineering and physics. In the literature, these polynomials are available in principal forms, which are the

physicist's Hermite polynomials $H_n(x)$ and the probabilist's Hermite polynomials $He_n(x)$. The physicists' Hermite polynomials arise particularly in solving some kinds of differential equations and in the solutions of the simple harmonic oscillator of quantum mechanics, while the probabilists' Hermite polynomials are used primarily in probability theory and statistics. See, for details, (Rainville 1960, Arfken and Weber 2005, Koornwinder et al. 2010, Abramowitz and Stegun 1972, Wikipedia 2005a); and also see the references cited therein. Moreover, in the literature, there are another kind of polynomials called Hermitian polynomials arising from the Hermite interpolation, and there are a few studies that associate some structural elements with the Hermitian polynomials for their finite element formulation and generate Hermitian shape functions for the analysis of the structural elements using the finite element method; for details and examples (among others), refer to (Augarde 1998).

The Rodrigues's formula for the physicist's Hermite polynomials is given by:

$$H_n(x) = (-1)^n e^{x^2} \frac{d^n}{dx^n} e^{-x^2} \tag{1}$$

and the relation between the physicist's and the probabilist's Hermite polynomials are given as below:

$$He_n(x) = 2^{-\frac{n}{2}} H_n\left(-\frac{x}{\sqrt{2}}\right), \tag{2}$$

(Abramowitz and Stegun 1972, Koornwinder et al. 2010, Weisstein 2005).

Note that the probabilist's Hermite polynomials are monic polynomials, and some of their values are listed below:

$$He_0(x) = 1,$$
$$He_1(x) = x,$$
$$He_2(x) = x^2 - 1,$$
$$He_3(x) = x^3 - 3x,$$
$$He_4(x) = x^4 - 6x^2 + 3,$$

and so on (Abramowitz and Stegun 1972, Koornwinder et al. 2010, Weisstein 2005).

The Gaussian function is given in the following form:

$$f(x) = e^{-x^2},$$

which is frequently used to represent the probability density function of the normal (Gaussian) distribution:

$$f(x, \mu, \sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}},$$

where μ denotes the mean (or expectation) of the distribution and σ^2 denotes the variance (while σ is the standard deviation of the distribution such that $\sigma \geq 0$). In the special case when $\mu = 0$ and $\sigma^2 = 1$, the probability density function reduces to

$$f(x, 0, 1) = \frac{e^{-\frac{x^2}{2}}}{\sqrt{2\pi}},$$

see, for details, (Squires 2012, Wikipedia 2005b); and also see the references cited therein.

Gaussian functions are extensively utilized across various fields. In statistics, they are key to describing normal distributions. In signal processing, they form the basis for Gaussian filters. Image processing uses two-dimensional Gaussians for effects like Gaussian blurs. Furthermore, in mathematics, they play a crucial role in solving heat and diffusion equations and in defining the Weierstrass transform. See, for details, (Squires 2012, Wikipedia 2005b); and also see the references cited therein.

Among others, the most interesting mathematical property of the function $f(x,\mu,\sigma)$ is that the derivatives of the Gaussian function can be expressed using the Hermite polynomials. Indeed, if x is replaced by $\frac{x-\mu}{\sigma\sqrt{2}}$ in the Rodrigues's formula, given by (1), for the Hermite polynomials, then the following relation is obtained:

$$H_n\left(\frac{x-\mu}{\sigma\sqrt{2}}\right) = (-\sigma\sqrt{2})^n e^{\frac{(x-\mu)^2}{2\sigma^2}} \frac{d^n}{dx^n} e^{-\frac{(x-\mu)^2}{2\sigma^2}}, \tag{3}$$

see, for details, (Romeny, 2003).

2 Main Results

In this section, the main findings of this study are given. Especially, relationships of the material-governing equations with the Hermite polynomials have been investigated.

Because of Rodrigues's formula, given by (1), for the Hermite polynomials and due to the equation (3), when the material's deflection is selected as

$$w(x,\mu,\sigma) := f(x,\mu,\sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}},$$

the material-governing equations can be rewritten in terms of the physicist's Hermite polynomials as follows:

$$\theta = EI\frac{d}{dx}\{w(x,\mu,\sigma)\} = -\frac{EI}{\sigma\sqrt{2}} H_1\left(\frac{x-\mu}{\sigma\sqrt{2}}\right) w(x,\mu,\sigma),$$

$$M = EI\frac{d^2}{dx^2}\{w(x,\mu,\sigma)\} = \frac{EI}{2\sigma^2} H_2\left(\frac{x-\mu}{\sigma\sqrt{2}}\right) w(x,\mu,\sigma),$$

$$V = EI\frac{d^3}{dx^3}\{w(x,\mu,\sigma)\} = -\frac{EI}{2\sqrt{2}\sigma^3} H_3\left(\frac{x-\mu}{\sigma\sqrt{2}}\right) w(x,\mu,\sigma)$$

and

$$q = EI\frac{d^4}{dx^4}\{w(x,\mu,\sigma)\} = \frac{EI}{4\sigma^4} H_4\left(\frac{x-\mu}{\sigma\sqrt{2}}\right) w(x,\mu,\sigma).$$

By using the relation, given by the equation (2), between the physicist's and the probabilist's Hermite polynomials, the other representations of the above material-governing equations have been obtained in the manner of the probabilist's Hermite polynomials as follows:

$$\theta = EI\frac{d}{dx}\{w(x,\mu,\sigma)\} = -\frac{EI}{\sigma} He_1\left(-\frac{x-\mu}{\sigma}\right) w(x,\mu,\sigma),$$

$$M = EI\frac{d^2}{dx^2}\{w(x,\mu,\sigma)\} = \frac{EI}{\sigma^2} He_2\left(-\frac{x-\mu}{\sigma}\right) w(x,\mu,\sigma),$$

$$V = EI\frac{d^3}{dx^3}\{w(x,\mu,\sigma)\} = -\frac{EI}{\sigma^3}He_3\left(-\frac{x-\mu}{\sigma}\right)w(x,\mu,\sigma)$$

and

$$q = EI\frac{d^4}{dx^4}\{w(x,\mu,\sigma)\} = \frac{EI}{\sigma^4}He_4\left(-\frac{x-\mu}{\sigma}\right)w(x,\mu,\sigma).$$

In the special case when $\mu = 0$ and $\sigma^2 = 1$, the above equations give us the following formulas:

$$\theta = -EIHe_1(-x)\frac{e^{-\frac{x^2}{2}}}{\sqrt{2\pi}} = \frac{xe^{-\frac{x^2}{2}}EI}{\sqrt{2\pi}},$$

$$M = EIHe_2(-x)\frac{e^{-\frac{x^2}{2}}}{\sqrt{2\pi}} = \frac{e^{-\frac{x^2}{2}}(x^2-1)EI}{\sqrt{2\pi}},$$

$$V = -EIHe_3(-x)\frac{e^{-\frac{x^2}{2}}}{\sqrt{2\pi}} = \frac{e^{-\frac{x^2}{2}}(x^3-3x)EI}{\sqrt{2\pi}}$$

and

$$q = EIHe_4(-x)\frac{e^{-\frac{x^2}{2}}}{\sqrt{2\pi}} = \frac{e^{-\frac{x^2}{2}}(x^4-6x^2+3)EI}{\sqrt{2\pi}}.$$

which are valid for the case when the function of materials' deflection is selected as

$$w(x,0,1) := f(x,0,1) = \frac{e^{-\frac{x^2}{2}}}{\sqrt{2\pi}}.$$

3 Conclusion

In line with the findings of this study, the following conclusions have been drawn:

In order to evaluate structural elements during the design phase of reverse engineering, it is necessary to know how they respond to different types of exposure. As is well known, different types of elements serving the same purpose may be subjected to different types of loads. The difficulties in calculations that take certain loading patterns into account and the fact that the calculations provide approximate values rather than precise and accurate values hinder the behavior of the elements from being clearly and accurately reflected in the designs. Therefore, the attempts described in the paper may help to overcome such shortcomings.

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EFFECT OF GAMMA RAYS APPLIED TO POLYMER MODIFIED MORTARS ON PHYSICO-MECHANICAL PROPERTIES

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ABSTRACT

This study investigates the effects of gamma irradiation on the physical–mechanical properties of mortars modified with styrene–acrylic ester (SAE) polymers. Prism specimens were produced at w/c=0.50 using PC CEM I 42.5R cement and crushed sand. Two SAE types were used at 5% and 10% replacements. After one week curing, part of the specimens was irradiated to a total gamma dose of 30 kGy. Flexural and compressive strengths were measured approximately one week after irradiation. The control sample exhibited the highest compressive strength. Increasing polymer content from 5% to 10% reduced both compressive and flexural strengths in irradiated and non-irradiated groups. Gamma irradiation generally decreased compressive strength (≈2–20%) while tending to increase flexural strength (≈4–9%). No systematic superiority was observed between STA and LIPATON. Overall, the findings suggest that gamma irradiation may enhance ductility/toughness but can limit compressive capacity in polymer-modified mortars, and that lower polymer dosages provide a more balanced mechanical response.

Keywords: Radiation shielding, polymer modified mortar, physico-mechanical properties

1 Introduction

Polymer-modified cement concrete or mortar is produced by mixing polymer dispersions, redispersible powders, water-soluble polymers, or liquid polymers with the fresh mix. Monomers can even be added to the mix, assuming polymerization and adequate film formation occur along with the cement hydration process (Mirza et al. 2002). In modern concrete production, composites produced using polymers together with cement and aggregates are called polymer-modified concrete, while composites made with polymers and aggregates are called polymer mortar (PM) or polymer concrete (PC). In this context, the performance of cementitious materials can be improved by adding particles small enough to fill the voids between cement particles.

Polymers have been used as additives and modifiers for cement-based materials such as mortar and concrete (Orange et al. 2007). The property development in mortar and concrete through polymer modification is related to the effect of the polymer on the material as a result of its incorporation into the material structure, cement hydration, porosity, and unit water content (Svegl et al. 2008). As a result, the chemical and physical interactions between polymers and cement hydrates significantly improve the strength, adhesion, resilience, impermeability, chemical resistance, and durability properties of mortar and concrete (Ohama 1987). These materials are suitable for use in various structural and non-structural precast products, such as tile adhesives, facade cladding, flooring, decorative coatings, and as repair materials in road buildings (Hwang and Young 2008).

Styrene-acrylic ester copolymer (SAE) plays an important role in the family of acrylic polymers used in cement mortars. When a suitable SAE emulsion is added to cement, the dynamic modulus of elasticity decreases with an increase in the SAE/cement ratio. Specific damping capacity, impact resistance, and abrasion resistance increase with an increase in the SAE/cement ratio. SAE-modified mortars exhibit the best dynamic behavior when the added polymer content is between 15-20% (Wong et al. 2003).

A minimum polymer/cement ratio of 5% is generally assumed to be necessary to ensure adequate film formation in mortar modified with polymer dispersions. Polymer film or polymer bridge formation is achieved in mortar modified with 10 to 15% styrene-acrylic ester (SAE) dispersion (Janotka et al. 1996). Film thickness and permeability to water molecules depend primarily on the type and percentage of polymer used. Strength reaches a maximum value around 5% and then gradually decreases.

The aim of this study is to investigate the effects of gamma ray exposure on the physical-mechanical properties of cement mortars modified with SAE at different ratios and to observe the differences that may occur with varying parameters such as gamma ray dose, w/c ratio, aggregate, and polymer type. Irradiation doses up to 50 kGy will be applied to minimize deterioration and maximize cross-linking. The morphological and thermal properties of the samples will also be examined to determine the effect of changing the dose on changes in material structure. Depending on all these, an optimization study and profit/cost analysis will also be carried out for the new material to be produced by evaluating the data obtained as a result of tests to be carried out in accordance with the standards in the building materials laboratory.

2 Materials and Methods

The volumetric mix designs of the mortar samples were prepared so that the cement, water, and aggregate amounts remained constant and that the mixture would fill 40 x 40 x 160 mm prism molds. For one prism sample, 145.2 dm^3 of cement, 225.0 dm^3 of water, and 629.8 dm^3 of

aggregate (crushed sand) were used. For this purpose, two separate sample groups were produced for two different styrene acrylic ester (SAE) polymer types, STA and LIPATON, with a w/c ratio of 0.5 and cement substitution rates of 5% and 10%. Table 1, showing the samples prepared for the test and their properties, is given below.

Table 1: Types of samples propered in the laboratory and some of their properties

Sample type	Properties
Cement	PC CEM I 42.5R, d=3.1 g/cm^3
Aggregate	Crushed sand (waited in a laboratory environment, sieved through a 4 mm sieve, 2.08% water absorption, d = 2.68 g/cm^3)
STA	Solid content 57%, pH=7.85, Tg=-10 °C, d=1.04 g/cm^3
LIPATON	solid content 47%, pH=10.00, Tg=-8 °C, d=1.02 g/cm^3

After the samples were poured into the molds, they were removed 24 hours later and left to cure in a water tank. After nearly one week of curing, some of the samples were stored in the laboratory before being carefully packaged and sent to GAMMA-PAK for irradiation.

The samples, irradiated to a total dose of 30 kGy, were subjected to flexural and compressive strength tests approximately one week after irradiation.

3 Results and Discussion

The results of the compressive and flexural strength tests are given in Table 2.

Table 2: Experimental values of the compressive and flexural strength

Sample code	Compressive Strength (MPa)	Flexural Strength (MPa)
STA 5%	43,56	7,45
STA 10%	33,88	6,90
LIPATON 5%	44,20	6,92
LIPATON 10%	36,56	6,79
STA 5% (irradiated)	35,02	6,66
STA 10% (irradiated)	32,95	7,16
LIPATON 5% (irradiated)	38,38	7,56
LIPATON 10% (irradiated)	31,46	7,28
CONTROL	47,62	7,34

As a result of the experiments,

- It was determined that the compressive strength value of control sample was measured higher than all of the others.

- It was observed that increasing the percentage polymer content from 5% to 10% resulted in lower flexural and compressive strength for both irradiated and non-irradiated groups compared to the control sample.
- Compressive strength values generally decreased following irradiation compared to non-irradiated samples.
- Flexural strength values generally increased following irradiation compared to non-irradiated samples.
- In light of all the data, no data pattern was detected in which polymers with different codes (STA and LIPATON) would show superiority or weakness over each other.

4 Conclusions

Studies on improving the performance of polymer-modified concrete through radiation exposure are a popular topic in the literature. In this study, it was observed that this exposure is more effective in flexural strength than in compressive strength.

In future studies, microstructural analyses will help to understand the reasons for these and similar findings, and the degree of improvement can be increased to higher levels.

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SÜPER KAPASİTÖR VE LİTYUM POLİMER PİLLERİN SABİT YÜK ALTINDA DEŞARJ ANALİZLERİNİN VERİMLİLİK AÇISINDAN KARŞILAŞTIRILMASI

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ÖZET

Enerji depolama teknolojileri, günümüzde artan enerji talebi, yenilenebilir enerji kaynaklarının entegrasyonu ve mobil sistemlerin yaygınlaşması nedeniyle kritik bir öneme sahiptir. Özellikle enerji sistemlerinde süreklilik, güvenilirlik ve verimlilik konuları depolama birimlerinin karakteristiklerine doğrudan bağlıdır. Bu çalışmada süperkapasitörler ile lityum polimer (Li-Po) pillerin sabit yük altında deşarj performansları ve enerji verimliliği yönünden kapsamlı bir karşılaştırma yapılmıştır. Bu çalışmada yöntem, ayrı ayrı süperkapasitör ve lityum polimer pillerin 13.8 volt seviyesine kadar şarj edilip aynı sabit yük altında bir deney düzeneği kurularak 10,5 volta kadar deşarj analizlerinin yapılması şeklinde belirlenmiştir. Gerçekleştirilen deneylerde sabit yük altında hem süperkapasitörler hem de Li-Po pillerin gerilim-zaman eğrileri, akım-zaman eğrileri, enerji kayıpları ve verimlilikleri analiz edilmiş, iki tip enerji depolama sistemi arasındaki fark verimlilik açısından ortaya konulmuştur. Ayrıca, son yıllarda öne çıkan enerji depolama araçlarından süperkapasitör ve lityum polimer piller ile ilgili son 15 yılda yapılmış çalışmalar, araştırma konusuna katkısı bakımından incelmiştir. Sonuç olarak; süperkapasitörlerin hızlı deşarj olma ve yüksek akım verebilme özelliği net olarak ortaya çıkmıştır. Li-Po pillerin ise süperkapasitörlere nazaran daha kısıtlı akım sağladığı ve daha uzun sürede deşarj olduğu görülmüştür. Öyle ki; 60 watt güç çeken bir yük altında süperkapasitör 13,8-10,5 volt aralığında yaklaşık 1 dakikada deşarj olurken, Li-Po pil yaklaşık 15 dakikalık süre boyunca yüke enerji sağlayabilmiştir. Ayrıca, süperkapasitörlerin ani güç çeken sistemlerde daha verimli çalıştığı, Li-Po pillerin ise stabil enerji gerektiren sistemlerde daha verimli olduğu ortaya konulmuştur. Bu bulgular çerçevesinde; süperkapasitörler ile Li-Po pillerin hibrit bir sistem içerisinde birlikte kullanılması daha verimli olacaktır.

Anahtar Kelimeler: süperkapasitör, Li-Po pil, verimlilik

COMPARISON OF DISCHARGE ANALYSIS OF SUPERCAPACITOR AND LITHIUM POLYMER BATTERIES UNDER CONSTANT LOAD IN TERMS OF EFFICIENCY

ABSTRACT

Energy storage technologies have critical importance due to the increasing energy demand in recent years, integration of renewable energy sources and proliferation of mobile systems. Especially, continuity, reliability and efficiency issue in energy systems are directly dependent on the characteristics of storage units. In this study, a comprehensive comparison was made between supercapacitors and lithium polymer (Li-Po) batteries in terms of discharge performance and energy efficiency under constant load. In this study, the method was determined as charging the supercapacitor and lithium polymer batteries separately up to 13.8 volts and performing discharge analyses up to 10.5 volts by setting up an experimental setup under the same constant load. In the experiments, voltage-time graphes, current-time graphes, energy losses and efficiencies of both supercapacitors and Li-Po batteries under constant load were analyzed and the difference between the two types of energy storage systems was revealed in terms of efficiency. In addition, studies conducted in the last 15 years on supercapacitors and Li-Po batteries, were examined in terms of their contribution to the research topic. As a result, the fast discharge and high current delivery properties of supercapacitors have been clearly revealed. It has been observed that Li-Po batteries provide more limited current and take longer to discharge than supercapacitors. While the supercapacitor was discharged in the 13.8-10.5 volt range in about 1 minute under a load drawing 60 watts of power, the Li-Po battery was able to provide energy to the load for about 15 minutes. Additionally, it has been shown that supercapacitors operate more efficiently in systems that draw sudden power, while Li-Po batteries are more efficient in systems that requiring stable energy. In the context of these findings, the combined use of supercapacitors and Li-Po batteries in a hybrid system would be more efficient.

Keywords: süpercapacitor, Li-Po batteries, efficieny

1.GİRİŞ

Günümüzde nüfusun artması, küresel ekonominin büyümesi, teknolojinin gelişmesi enerji tüketiminin artmasında etkili olmaktadır (Sorrell, 2015). Uluslararası Enerji Ajansı verilerine göre, küresel enerji ihtiyacının 2050 yılına kadar %50 den fazla artacağı tahmin edilmektedir (IEA, 2022). Bu durum, sürdürülebilir ve verimli enerji kaynaklarına yönelimi arttırmakta ve enerji depolama tekniklerinin stratejik önemini ortaya koymaktadır. Bu nedenle, enerji depolama sistemleri enerji sürekliliğini sağlamak konusunda kritik bir rol üstlenmektedir (Luo at al., 2015).

Enerji depolama sistemleri arasında elektrokimyasal birimler (aküler, lityum-iyon, lityum polimer vb.) ile elektriksel depolama birimleri (süperkapasitör, manyeto-dinamik sistemler) öne çıkmaktadır (Miller&Simon, 2008; Burke, 2010). Bu bağlamda, son yıllarda **süper kapasitörler** ve **lityum polimer (Li-Po) piller**, farklı uygulamalarda yüksek performans ve uzun ömürlü enerji depolama çözümleri olarak ön plana çıkmıştır (Gopi & Ramesh, 2024).

Süper kapasitörler, klasik kondansatörler ile elektrokimyasal piller arasında konumlanan ve enerji depolama mekanizması bakımından her iki sistemin özelliklerini bir araya getiren elemanlardır. Temel olarak enerji depolama, çift katmanlı kapasitans (EDLC) veya psödokapasitans mekanizmalarıyla sağlanır (Chen, 2024). EDLC tipi süperkapasitörlerde enerji, elektrot-elektrolit ara yüzeyinde elektrostatik yük birikimiyle depolanırken; psödokapasitörlerde iyonik reaksiyonlar da sürece dâhil olur. Bu nedenle, elektrot malzemesi, yüzey alanı, gözeneklilik ve elektrolit seçimi sistemin enerji yoğunluğunu ve deşarj verimliliğini doğrudan etkilemektedir (Khan, 2025).

Lityum polimer (Li-Po) piller, yüksek enerji yoğunlukları, düşük ağırlıkları ve tasarım esneklikleri sayesinde taşınabilir elektronik cihazlardan elektrikli araçlara kadar geniş bir kullanım alanına sahiptir (Cortada-Torbellino et al., 2024). Bu piller, lityum iyon pillerle benzer prensipte çalışmakla birlikte, sıvı yerine polimer bazlı elektrolitler kullanmaları sebebiyle daha güvenli ve kompakt çözümler sunmaktadır. Ancak yüksek akım çekimi durumunda iç direnç artışı, ısınma ve kapasite düşüşü gibi verimlilik kayıpları meydana gelmektedir (Hasan, 2025).

Süperkapasitörler yüksek güç yoğunluğunda anlık enerji sağlayabilmeleri, uzun çevrim ömrü ve hızlı şarj-deşarj özellikleri ile dikkat çekerken; Li-Po piller yüksek enerji yoğunluğu, taşınabilirlik ve düşük maliyet avantajı gibi özellikleriyle öne çıkmaktadır (Conway, 1999; Chen, 2009). Süperkapasitörler; elektrikli hibrit araçlar, taşınabilir elektronik cihazlar, rüzgar ve güneş enerjisi sistemleri gibi alanlarda yoğun olarak kullanılmaktadır (Balbaşı, Şahin, 2015). Li-Po piller ise dron ve multikopter vb insansız hava araçları, ölçüm cihazları, tıbbi cihazlar, robotik ve endüstriyel sistemler gibi alanlarda oldukça yaygınlaşmaktadır (Gelen, Tüfekçioğlu, 2020; Lee et al., 2012).

Bu çalışmanın amacı, yüksek güç yoğunluğu ile öne çıkan süperkapasitörler ile yüksek enerji yoğunluğu ile dikkat çeken lityum polimer (Li-Po) pillerin sabit yük altında deşarj performanslarının deneysel yollarla analiz edilerek verimlilik açısından karşılaştırılmasıdır. Bu doğrultuda deneysel düzenek oluşturularak gerilim ve akım karakteristikleri, enerji kayıpları ve verimlilik değerleri analiz edilmiştir. Çalışma sonucunda elde edilen bulgular, enerji depolama sistemlerinin gelecekteki kullanım alanlarına rehberlik edecek ve sürdürülebilir enerji sitemlerinin kullanımı için önemli bir yol haritası oluşturacaktır.

Süperkapasitörler ile Li-Po pillerin değişken yük profilleri veya farklı sıcaklık koşulları açısından performans analizleri literatürde ayrı ayrı yer bulmuş olsa da, bu iki depolama sisteminin sabit yük altındaki deşarj performanslarının deneysel yolla karşılaştırıldığı çalışmalar sınırlı sayıdadır. Bu çalışma, süperkapasitör ve lityum polimer pillerin sabit yük

altında enerji verimliliği, güç kayıpları ve deşarj davranışlarının deneysel olarak karşılaştırılmasını hedefleyerek literatürdeki önemli bir boşluğu doldurmayı amaçlamaktadır.

Bu çalışma, enerji verimliliği odaklı sistem tasarımlarında doğru depolama teknolojisinin belirlenmesine yönelik mühendislik uygulamalarına katkı sağlayacak olması bakımından önemlidir.

Bu çalışmanın özgünlüğü, süperkapasitör ve Li-Po pillerin sabit yük altında deşarj performanslarına dayanarak verimlilik açısından bütüncül bir karşılaştırma sağlayan ve deneysel bir çerçeve sunan yaklaşımıdır.

2. MATERYAL VE METOT

Bu bölümde, süperkapasitör ve lityum polimer (Li-Po) pillerin sabit yük altında deşarj performanslarının karşılaştırılması amacıyla oluşturulan deneysel düzenek ve uygulanan yöntemler ayrıntılı biçimde açıklanmaktadır.

2.1. Deneysel Düzenek

Bu çalışmada iki farklı enerji depolama birimi incelenmiştir:

1. **Süperkapasitör grubu,**
2. **Lityum polimer (Li-Po) pil paketi.**

Her iki sistem de aynı test koşullarına tabi tutulmuş, başlangıç gerilimi **13,8 V** olacak şekilde şarj edilmiş ve sabit yük altında deşarj edilmiştir. Böylece farklı enerji depolama teknolojilerinin aynı başlangıç koşullarında enerji verimliliği açısından karşılaştırılması sağlanmıştır.

2.1.1. Süperkapasitör Sistemi

Deneyin ilk aşamasında, altı adet **500 Farad, 2.7 V** nominal değerlere sahip süperkapasitör seri olarak bağlanmıştır. Bu bağlantı sonucunda sistemin toplam kapasitesi yaklaşık **83,3 F**, toplam çalışma gerilimi ise **16,2 V** olmuştur. Her bir kapasitörün iç direnci **1,7 miliohm (mΩ)** olduğundan, sistemin toplam iç direnci yaklaşık **10,2 mΩ** olarak hesaplanmıştır.

Süperkapasitör grubu **13,8 V** gerilime kadar şarj edilmiştir. Şarj işlemi sabit akım–sabit gerilim prensibiyle gerçekleştirilmiş, hedef gerilime ulaşıldığında akım sıfıra yaklaşana kadar şarj devam ettirilmiştir.

Deşarj deneyinde, süperkapasitör grubunun çıkışına **voltaj, akım ve güç** değerlerini anlık olarak ölçebilen bir dijital veri toplama cihazı bağlanmıştır. Ölçüm cihazının ardından **60 W gücünde, 12 V halojen otomobil far ampulü** sabit yük olarak devreye alınmıştır. Ampulün sabit direnci, deşarj boyunca kapasitör geriliminin düşmesiyle birlikte akımın azalmasını doğal olarak sağlamış ve tipik bir sabit yük profili elde edilmiştir.

2.1.2. Lityum Polimer Pil Sistemi

İkinci deneysel sistem, **14,8 V – 4200 miliamper (mAh) – 40C** özelliklerine sahip bir **Li-Po pil paketi** kullanılarak oluşturulmuştur. Pilin üretici verilerine göre iç direnci **50 mΩ'**dür. Bu değer, süperkapasitör sistemine kıyasla daha yüksek olup, özellikle yüksek akım altında ısıl kayıpların oluşmasına neden olmaktadır.

Li-Po pil de süperkapasitör sistemine benzer şekilde **13,8 V** gerilime kadar şarj edilmiştir. Böylece her iki enerji kaynağı aynı başlangıç potansiyeline sahip olacak biçimde test edilmiştir.

Pil çıkışına süperkapasitör sisteminde kullanılanla aynı **voltaj, akım ve güç ölçüm cihazı** bağlanmış, ardından aynı **60 Watt halojen ampul** sabit yük olarak devreye alınmıştır. Böylece deney koşulları arasında ölçüm altyapısı ve yük açısından tam eşdeğerlik sağlanmıştır.

2.1.3. Ölçüm Koşulları ve Veri Toplama

Tüm deneyler **25 ± 1 °C** sıcaklıkta sabit ortam koşullarında gerçekleştirilmiştir. Her iki sistem 13.8 V şarj durumuna getirildikten sonra, sabit yük altında **deşarj süreci başlatılmış** ve sistem gerilimi 10,5 V seviyesinin altına düşene kadar ölçümler sürdürülmüştür.

Ölçüm cihazı, deşarj süresince **gerilim (V), akım (A), güç (W)** ve **zaman (s)** değerlerini saniyelik örnekleme aralığıyla kaydetmiştir. Toplanan veriler bilgisayar ortamına aktarılarak, enerji verimliliği, güç kayıpları ve gerilim düşüm eğrileri MATLAB ortamında analiz edilmiştir.

2.2. Verilerin Değerlendirilmesi

Deneysel veriler, hem anlık ölçümler hem de bütünleşik (integral) enerji analizi yöntemiyle değerlendirilmiştir. Süperkapasitör ve Li-Po pil sistemlerinin enerji verimlilikleri (η) aşağıdaki eşitlik yardımıyla hesaplanmıştır:

$$\eta = \frac{E_{yük}}{E_{kaynak}}\ x\ 100$$

Burada $E_{yük}$, yük tarafından harcanan toplam enerji miktarını; E_{kaynak}, enerji depolama birimi tarafından sağlanan toplam enerjiyi ifade etmektedir.

Her iki sistem için deşarj süresince **gerilim-zaman** ve **güç-zaman** eğrileri çıkarılmış, bu eğrilerin integrali alınarak toplam enerji miktarları hesaplanmıştır. Ayrıca, iç direnç kaynaklı kayıplar gerilim düşüm eğrilerinden belirlenmiştir.

Temel varsayımlar:

- Sabit yük: 60 W, 12 V nominal halojen araba ampulü. Ampulün sabit direnç olarak kabul edilmesi:

$R_{yük} = \frac{V_{yük}^2}{P_{yük}} = \frac{12^2}{60} = 2{,}4\ \Omega.$

- Deşarj sonlandırma koşulu: **kaynak (paket) gerilimi 10,50 V** altına düştüğünde test sonlandırılıyor.
- Ölçümlere başlangıçta **her iki kaynak da 13,8 V** olacak şekilde şarj edildi.
- Süperkapasitör paketi: 6 × 500 F (seri).

Seri toplam kapasitans: C_{toplam} = 500 / 6 ≈ 83,333 F

Her bir ESR = 1,7 mΩ

Seri ESR toplamı: R_{ESR} = 1,7 mΩ = 10,2 mΩ

- Li-Po paketi:

Başlangıç gerilimi Vi = 13,8 V,

Kapasite 4200 mAh (4,2 Ah),

İç direnç R_{ESR} = 50 mΩ = 0,05 Ω.

2.2.1.Süperkapistör Hesapları (Sayısal Sonuçlar)

Parametreler:

- Ctoplam = 83,333 F
- R_{ESR} = 0,0102 Ω
- $R_{yük}$ = 2,4 Ω
- Toplam seri direnç $R_{toplam} = R_{yük} + R_{ESR}$ = 2,4102 Ω
- Başlangıç gerilimi V_i = 13,8 V

Zaman sabiti :

$$\tau = C_{toplam} . R_{toplam} \approx 83{,}333 \times 2{,}4102 \approx 200{,}85 \text{ s.}$$

Deşarj süresi (kapasitör gerilimi $V_{cap}(t) 13{,}8\, V \rightarrow 10{,}5\, V\ olana\ kadar$):

$$t_{son} = \tau \ln\left(\frac{V_{cap}}{V_{son}}\right) = 200{,}85 \ln\left(\frac{13{,}8}{10{,}5}\right) \approx 54{,}9 \text{ s.}$$

Başlangıç akımı:

$$I_i = \frac{V_i}{R_{toplam}} \approx \frac{13{,}8}{2{,}4102} \approx 5{,}726 \text{ A.}$$

Başlangıçtaki yük gücü (yaklaşık):

$$P_{0,yük} = I_i^2 R_{yük} \approx (5{,}726)^2 \times 2{,}4 \approx 78{,}9 \text{ W.}$$

(Not: Halajen ampül direnci sabit olduğu için başlangıçta 60w üzerinde yük çekebilir; Ampülün gücü 12v 60w olduğundan başlangıçta 13,8v gerilim varken daha yüksek güç oluşur; burada ampül geriliminin üzerindeki çalışması kısa süreli kabul edilebilir.)

Toplam yük tarafından alınan enerji ($0 \rightarrow t_{son}$) (integral hesabı ile):

$$E_{yük} \approx 3{,}327 \times 10^3 J \approx 0{,}9247 \text{ Wh}$$

Kaynak (kapasitör)tarafından sağlanan enerji:

$$E_{kaynak} \approx 3{,}341 \times 10^3 J \approx 0{,}9281 \text{ Wh}$$

ESR kaynaklı kayıp:

$$E_{ESR_kaybı} = E_{kaynak} - E_{yük} \approx 14{,}14 \quad J$$

Verimlilik (belirtilen deşarj koşullarında):

$$\eta_{SC} = \frac{E_{yük}}{E_{kaynak}} \approx \frac{33217{,}11}{3341{,}25} \approx 0{,}9958 \rightarrow 99{,}6\%$$

Süperkapasitör için Veri Özeti:

- Deşarj süresi $(13{,}8\, V \rightarrow 10{,}5\, V) \approx 54{,}9\, s\ (\sim 0{,}915\ dakika)$
- Başlangıç akımı: ≈5,73 A
- Yük tarafından alınan enerji: ≈3,327 kj (≈0,925 Wh)
- ESR kaybı: ≈14,14 J
- Verimlilik (enerji bazında): ≈ 99,6 %

2.2.2. Li-Po pil hesapları

Li-Po paketin **başlangıç gerilimi'nin** deşarjla yavaşça azaldığını kabul ederek; 13,8 V başlangıçtan **10,731 Volt** değerine kadar başlangıç gerilimi lineer düştüğünde terminal geriliminin 10,50 V olacağını hesaplanmıştır. Bu yöntem net bir mühendislik kestirimidir ve aşağıdaki adımlarla izlenerek hesaplanmıştır.

Hesap adımları:

-$R_{ESR} = 0{,}05\ \Omega, \mathrm{R}_{yük} = 2{,}4\ \Omega \rightarrow$ toplam $\mathrm{R} = 2{,}45\ \Omega$

-Başlangıç akımı yaklaşık: $\mathrm{I_i} \approx \frac{13{,}8}{2{,}45} \approx 5{,}633$ A.

-Terminal gerilimi $V_{yük} = I \cdot R_{yük}$

Terminalın 10,5 V olabilmesi için gerekli $\mathrm{V_i}$ değeri ters çözülerek:

$$Vo_{son} = 10{,}5 \cdot \frac{R_{yük}+R_{ESR}}{R_{yük}} \approx 10{,}731\ \mathrm{V}.$$

-Başlangıç gerilimi'nin 13,8 V ile 10,713 V arasındaki azalma, toplam kapasitenin bir kısmının tüketilmesine karşılık gelir.

-Tam deşarj süresi (sabit akım varsayımıyla) $T_{full} \approx \frac{4{,}2\ Ah}{5{,}633\ A} \approx 0{,}7458$ saat ≈ 2685 saniye

Fakat biz 10,5 volta kadar yani %35 lik bir kısmı deşarj edeceğiz

-Bu nedenle $t_{son} \approx 0{,}35 \times \mathrm{T}_{full} \approx 939$ saniye (≈ 15 dakika)

Li-Po pil için Veri Özeti:

- Deşarj süresi $\left(13{,}8\ V \rightarrow\ V_{yük} = 10{,}5\ V\right)$: $t_{son} \approx 939$ saniye (≈ 15 dakika)
- Yük tarafından alınan toplam enerji: $\mathrm{E_{yük}}$ ≈36,57 kJ≈10,04 Wh
- Kaynak (pil) tarafından sağlanan enerji: $\mathrm{E_{kaynak}}$ ≈ 36,910 kJ
- İç direnç kaybı: $\mathrm{E_{ESR_kaybı}}$ ≈753 J
- Verimlilik (enerji bazında):

$$\eta_{Li-Po} = \frac{E_{yük}}{E_{kaynak}} \approx \frac{36157}{36910} \approx \%97{,}96$$

Bulgulara göre karşılaştırmalı özet tablo aşağıda verilmiştir (Tablo 1):

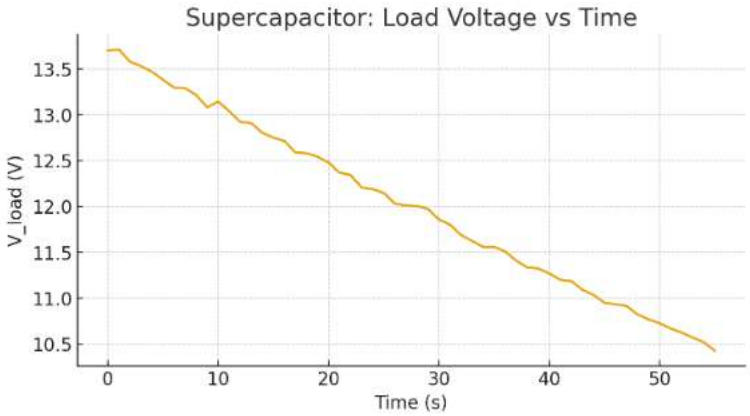
Tablo1. Deney bulgularına göre süperkapasitör ile Li-Po pillerin performans parametreleri bakımından karşılaştırılması

Ölçüt	Süperkapasitör (SC)	Li-Po Pil
Başlangıç akımı	5,73A	5,63A
Başlangıç yük gücü	~78,9W	~77,6 W
Deşarj süresi ($\rightarrow 10{,}5\ V$)	≈54,9 saniye(≈0,92 dakika)	≈939 saniye(≈15 dakika)
Yük tarafından alınan enerji	≈3,327 kJ (≈0,925 Wh)	≈36,16 kJ (≈10,04 Wh)
Kaynağın verdiği enerji	≈3,341 kJ	≈36,91 kJ

İç direnç/ESR kaybı	≈14,14 J	≈753 J
Enerji verimliliği	≈%99,6	≈%98,0

2.2.3.Sonuçlara Dayanarak Yapılan Yorumlar ve Çıkarımlar

- Süperkapasitör **çok kısa sürede** yüksek güç verebiliyor; burada deşarj süresi sadece ~55 s olarak çıktı. Bu, süperkapasitörün **yüksek güç- düşük enerji** karakterini gösterir: çok kısa süre içinde enerji verir ancak toplam enerji (Wh) düşüktür.
- Li-Po pil, aynı başlangıç geriliminde çok daha uzun süre enerji verebiliyor (~15 dakika bu koşulda) ve yükün ihtiyaç duyduğu toplam enerjide belirgin üstünlük sağlıyor (≈10 Wh vs ≈0,93 Wh). Bu da Li-Po'nun **enerji yoğunluğu** bakımından avantajını gösterir.
- Verimlilik açısından her iki cihaz da bu koşullarda yüksek verimlilik göstermektedir; süperkapasitörde hesaplanan verimlilik çok yüksek (~%99,6) çünkü ESR çok küçük ve test kısa sürüyor. Li-Po'da iç direnç daha yüksek olduğundan (50 mΩ) kayıplar daha büyüktür ama yine de bu yük/güç profili için yaklaşık %98 verim çıktı.
- Gerçekte halojen ampul sabit **güç** (60 W) yerine sabit **direnç** yüküdür; bu nedenle başlangıçta ampul, nominalinden farklı güç çekebilir — ölçümlerde ampulün gerçek güç eğrilerini kaydetmek (anlık V ve I) önemlidir — burada yaptığımız hesapta ampul ideal dirençle modelledi.



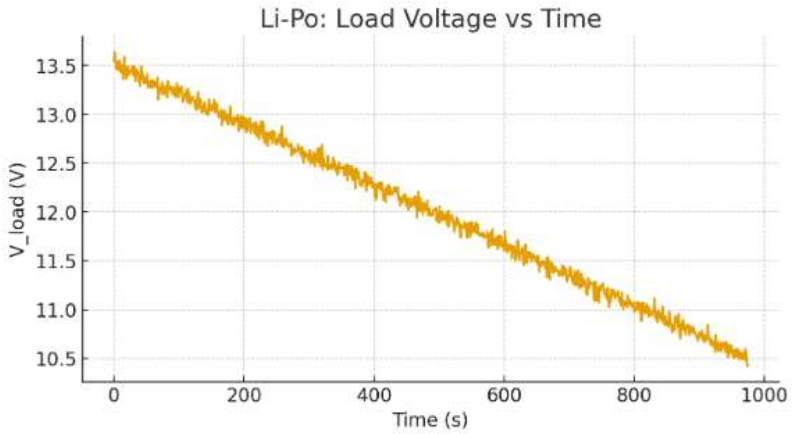
Şekil1. Süperkapasitörün gerilim-zaman grafiği



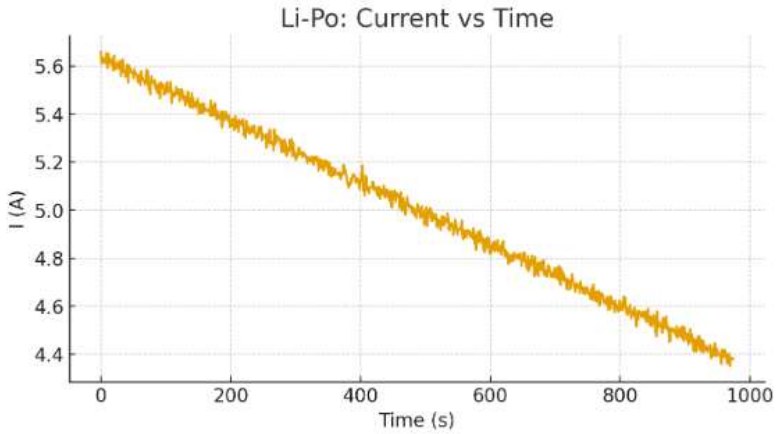
Şekil 2. Süperkapasitörün akım-zaman grafiği



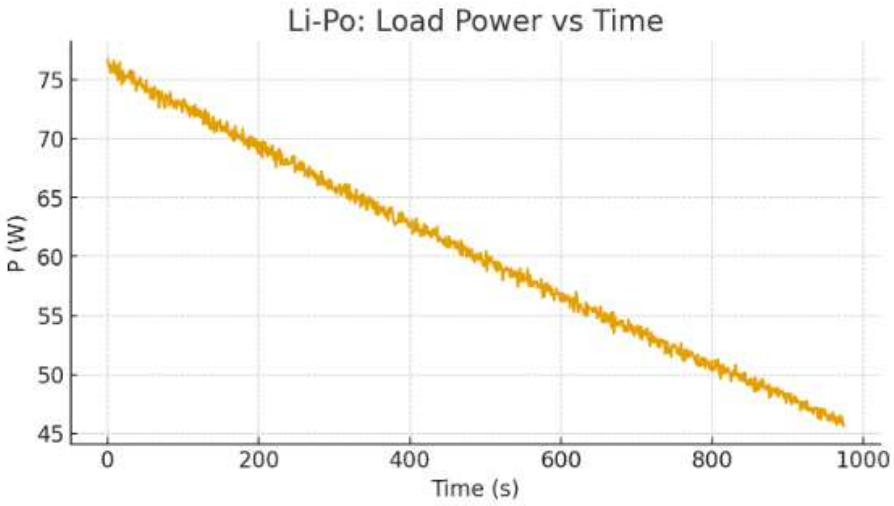
Şekil 3. Süperkapasitörün güç-zaman grafiği



Şekil 4. Li-Po pilin gerilim-zaman grafiği



Şekil 5. Li-Po pilin akım-zaman grafiği



Şekil 6. Li-Po pilin güç-zaman grafiği

Elde edilen verilerin özeti aşağıda sıralanmıştır.

- Süper kapasitör deşarj serisi: yaklaşık **55 s** (13,8 V → ~10,49 V load).
  - Yük tarafından alınan enerji ≈ **0.9257 Wh**.
  - Kaynak tarafından sağlanan enerji ≈ **0.9295 Wh**.
  - İç direnç/ESR kaybı ≈ **0.00386 Wh**.
  - Başlangıç akımı ≈ **5.73 A**.
- Li-Po pil deşarj serisi: yaklaşık **939s** (13,8 V → ~10,45 V load).
  - Yük tarafından alınan enerji ≈ **16.3427 Wh**.
  - Kaynak tarafından sağlanan enerji ≈ **16.6803 Wh**.
  - İç direnç kaybı ≈ **0.3376 Wh**.
  - Başlangıç akımı ≈ **5.66 A**.

3. BULGULAR VE TARTIŞMA

Bu bölümde, süper kapasitör ve lityum polimer (Li-Po) pil sistemlerinin sabit yük altında deşarj davranışları, enerji verimlilikleri ve iç direnç kaynaklı kayıplar karşılaştırmalı olarak incelenmiştir. Her iki enerji kaynağı da 13,8 V gerilim değerine kadar şarj edilmiştir. Deneylerde her iki sistemin çıkışına 60 W gücünde, 12 V nominal değerlere sahip halojen otomobil ampulü yük olarak bağlanmıştır. Ölçümler, gerilim (V), akım (A) ve güç (W) parametreleri üzerinden saniyelik örnekleme ile gerçekleştirilmiştir.

3.1. Süper Kapasitör Sisteminin Deşarj Davranışı

Süper kapasitör grubu 13,8 V'tan başlayarak yaklaşık **55 saniye** içinde 10,5 V seviyesine kadar deşarj olmuştur. Bu süreçte, başlangıç akımı ortalama **5,73 A**, ortalama güç değeri ise **yaklaşık 57 W** olarak ölçülmüştür. Gerilim–zaman eğrisi incelendiğinde (Şekil 2), kapasitör geriliminin deşarj süresince üstel bir biçimde azaldığı gözlenmiştir.

Deşarj süresince yük tarafından harcanan toplam enerji **0,93 Wh**, kaynak tarafından sağlanan toplam enerji ise **0,93 Wh** olarak hesaplanmıştır. İç direnç (ESR) kaynaklı enerji kaybı yaklaşık

0,0039 Wh düzeyinde gerçekleşmiştir. Bu durum, süper kapasitörlerin yüksek akım çekilmesine rağmen düşük enerji kayıplı bir yapı sergilediğini göstermektedir.

Kapasitörlerin kısa sürede deşarj olması, yüksek **güç yoğunluğu (power density)** özelliğini doğrulamaktadır. Ancak enerji yoğunluğunun düşük olması nedeniyle, bu tür enerji depolama elemanlarının uzun süreli yük beslemelerinde tek başına yeterli olamayacağı görülmektedir (Burke, 2007).

3.2. Lityum Polimer Pil Sisteminin Deşarj Davranışı

Li-Po pil 13,8 V'tan başlayarak yaklaşık **939 saniye** (yaklaşık 15 dakika) sürede 10,4 V seviyesine kadar deşarj olmuştur. Başlangıç akımı **5,66 A**, ortalama güç ise yaklaşık **56 W** seviyesindedir. Gerilim düşümü süper kapasitöre kıyasla çok daha yavaş gerçekleşmiş; deşarj süresi boyunca eğrinin neredeyse lineer karakterde olduğu gözlemlenmiştir (Şekil 5).

Deşarj süresince yük tarafından alınan enerji **16,34 Wh,** kaynak tarafından sağlanan enerji **16,68 Wh** olarak hesaplanmıştır. İç direnç kaynaklı kayıplar **0,34 Wh** düzeyindedir. Bu durum, Li-Po pilin enerji yoğunluğunun oldukça yüksek olduğunu, ancak iç direnç nedeniyle oluşan ısıl kayıpların süper kapasitöre göre belirgin şekilde fazla olduğunu göstermektedir (Arora & Zhang, 2004).

3.3. Karşılaştırmalı Değerlendirme

Her iki enerji kaynağının temel performans parametreleri Tablo 2'de özetlenmiştir. Süper kapasitör sistemi, **yüksek güç çıkışı** ve **düşük enerji kapasitesi**, Li-Po sistemi ise **yüksek enerji kapasitesi** ve **daha uzun deşarj süresi** ile öne çıkmaktadır.

Tablo 2. Süperkapasitör ile Li-Po pillerin temel performans parametreleri bakımından karşılaştırılması

Parametre	Süperkapasitör	Li-Po Pil
Başlangıç Gerilimi (V)	13,8	13,8
Deşarj sonu gerilim	10,5	10,5
Deşarj süresi (s)	55	939
Yüke aktarılan enerji (Wh)	0,93	16,34
Kaynaktan sağlanan enerji (Wh)	0,93	16,68
İç direnç kaybı (Wh)	0,0039	0,34
Başlangıç akımı (A)	5,73	5,66

Süper kapasitörün yüksek deşarj akımı sayesinde kısa sürede enerji aktarımı yaptığı, buna karşılık enerji depolama kapasitesinin sınırlı kaldığı tespit edilmiştir. Li-Po pil ise uzun süre boyunca sabit güç sağlayarak daha istikrarlı bir performans göstermiştir.

Enerji verimliliği bakımından süper kapasitör sisteminin %99,6, Li-Po pil sisteminin ise %98 civarında bir enerji dönüşüm verimi elde edilmiştir. Her iki sistemin verimlilikleri oldukça yüksek olmasına rağmen, Li-Po pildeki iç direnç kaynaklı ısıl kayıpların daha belirgin olduğu gözlemlenmiştir.

Bu bulgular, süper kapasitörlerin kısa süreli, yüksek akım gerektiren uygulamalarda (ör. elektrikli araçlarda ani hızlanma veya rejeneratif frenleme) avantajlı olduğunu; Li-Po pillerin

ise uzun süreli enerji ihtiyacı gerektiren uygulamalarda (ör. drone veya mobil enerji sistemleri) daha uygun olduğunu göstermektedir (Conway, 1999; Chen et al., 2020).

3.4. Enerji Verimliliği ve Kayıp Analizi

Gerilim–akım eğrilerinin integrali üzerinden yapılan hesaplamalarda, her iki sistem için de toplam enerji girdisi ve yük tarafına aktarılan enerji miktarları belirlenmiştir. Süper kapasitördeki kayıplar, düşük ESR sayesinde minimum düzeyde kalmıştır. Li-Po pillerde ise iç direnç, sıcaklık artışıyla birlikte artmakta ve bu da enerji dönüşüm verimini düşürmektedir (Plett, 2015).

Ayrıca, süper kapasitörlerin hızlı deşarj sonrası geriliminin aniden düşmesi, enerji yönetim sistemlerinde gerilim regülasyonu ihtiyacını ortaya koymaktadır. Li-Po pillerde bu gereksinim daha az belirgindir; çünkü gerilim değişimi daha yavaş ve öngörülebilirdir.

3.5. Genel Değerlendirme

Deneysel bulgular sonucunda;

- Süper kapasitörler **yüksek güç yoğunluğu, düşük iç direnç ve yüksek çevrim ömrü** ile öne çıkmaktadır.
- Li-Po piller **yüksek enerji yoğunluğu, uzun süreli güç sağlama** ve **stabil gerilim davranışı** açısından avantajlıdır.
- Her iki teknolojinin **hibrit kombinasyonu**, enerji depolama sistemlerinde hem ani güç ihtiyacını hem de uzun süreli enerji ihtiyacını karşılamak için ideal bir çözüm oluşturabilir (Zhang et al., 2022).

4. SONUÇLAR VE ÖNERİLER

Bu çalışmada, süper kapasitör ve lityum polimer (Li-Po) pillerin sabit yük altında deşarj davranışları deneysel olarak incelenmiş, iki enerji depolama teknolojisi **enerji verimliliği, güç yoğunluğu ve iç direnç kaynaklı kayıplar** açısından karşılaştırılmıştır. Her iki enerji kaynağı da 13,8 V gerilime kadar şarj edilmiş ve aynı yük (60 W halojen ampul) altında test edilmiştir.

Elde edilen bulgular, her iki sistemin farklı enerji gereksinimlerine yönelik avantaj ve sınırlamalarını açıkça ortaya koymuştur.

4.1. Sonuçlar

1. **Süper kapasitör sistemi**, kısa sürede yüksek akım ve güç sağlayabilmiş, yaklaşık **55 saniye** içinde 13,8 V'tan 10,5 V seviyesine düşmüştür.
   - Yüke aktarılan enerji **0,93 Wh**, toplam enerji verimliliği yaklaşık **%99,6** olarak bulunmuştur.
   - Düşük ESR (1,7 mΩ) değeri sayesinde enerji kayıpları son derece az gerçekleşmiştir.
   - Ancak düşük enerji yoğunluğu nedeniyle uzun süreli enerji ihtiyacını karşılayamamaktadır.
2. **Li-Po pil sistemi**, yaklaşık **974 saniye** sürede gerilimini 13,8 V'tan 10,5 V'a düşürmüş ve yükü uzun süre besleyebilmiştir.
   - Yüke aktarılan enerji **16,34 Wh**, toplam verimlilik **%98 civarında** hesaplanmıştır.

- Pilin 50 mΩ iç direnci, süper kapasitöre kıyasla daha yüksek kayıplara neden olmuş (**0,34 Wh**).
- Gerilim-zaman eğrisi süper kapasitöre göre daha lineer bir davranış sergilemiştir.

3. **Enerji verimliliği karşılaştırması** sonucunda, süper kapasitörün daha düşük enerji kaybı sergilediği; Li-Po pilin ise enerji depolama kapasitesi bakımından üstün olduğu belirlenmiştir.

4. Her iki enerji kaynağının da benzer akım değerlerinde çalıştırılmasına rağmen, **deşarj süresi farkı yaklaşık 18 kat** olarak ölçülmüştür. Bu fark, Li-Po pilin kapasite (Ah) ve enerji yoğunluğu (Wh/kg) açısından süper kapasitöre kıyasla çok daha avantajlı olduğunu göstermektedir.

5. **Güç profilleri** karşılaştırıldığında, süper kapasitörün başlangıçta yüksek güç çıkışı sağladığı, Li-Po pilin ise bu gücü daha uzun süre boyunca koruduğu gözlemlenmiştir.

4.2. Genel Değerlendirme

Elde edilen sonuçlar, enerji depolama sistemlerinin kullanım amacına göre seçilmesi gerektiğini göstermektedir. Süper kapasitörler **yüksek güç, kısa süreli enerji** gereksinimlerinde; Li-Po piller ise **uzun süreli enerji ve düşük güç yoğunluğu** gerektiren uygulamalarda daha uygundur.

Bu nedenle, iki teknolojinin **hibrit enerji depolama sistemi** (HESS – *Hybrid Energy Storage System*) olarak birlikte kullanılması, hem anlık güç ihtiyacının hem de uzun süreli enerji ihtiyacının dengeli bir biçimde karşılanmasını sağlayabilir. Özellikle elektrikli araçlar, yenilenebilir enerji destekli mikroşebekeler ve kesintisiz güç kaynakları gibi uygulamalarda bu yaklaşım yüksek performans potansiyeli sunmaktadır (Zhang et al., 2022).

4.3. Öneriler

1. **Süper kapasitör – Li-Po hibrit sistem tasarımı:**
Her iki enerji kaynağının paralel bağlandığı, akım paylaşımını aktif olarak yöneten bir kontrol devresiyle hibrit sistem oluşturulabilir. Bu yapı, hem enerji yoğunluğunu hem de güç yoğunluğunu artıracaktır.

2. **Isıl yönetim çalışmaları:**
Li-Po pillerde iç direnç kaynaklı kayıpların ısıl etkileri ayrıntılı olarak incelenmeli; sıcaklık artışına karşı koruma devreleri optimize edilmelidir.

3. **Gerçek zamanlı enerji yönetim algoritmaları:**
Süper kapasitörün hızlı tepki verme özelliği, Li-Po pilin yavaş ancak kararlı karakteriyle birleştirildiğinde, akıllı kontrol algoritmalarıyla sistemin genel verimliliği artırılabilir.

4. **Farklı yük profilleri altında testler:**
Gelecek çalışmalarda, sabit yük yerine dinamik yük (örneğin değişken motor veya inverter yükleri) altında sistemlerin performansı incelenmelidir.

5. **Yaşlanma (degradasyon) analizi:**
Süper kapasitör ve Li-Po pillerin uzun süreli çevrim ömürleri karşılaştırılmalı; kapasite kaybı, ESR artışı ve verimlilik düşüşü gibi parametreler deneysel olarak gözlemlenmelidir.

4.4. Genel Sonuç

Bu çalışma, süper kapasitörlerin ve Li-Po pillerin sabit yük altında farklı enerji davranışlarını deneysel olarak ortaya koymuş ve her iki sistemin mühendislik uygulamalarındaki rollerini belirlemiştir. Süper kapasitörler, ani güç gerektiren durumlarda ideal bir çözüm sunarken; Li-Po piller, enerji sürekliliği gereken senaryolarda vazgeçilmez bir enerji kaynağı olarak değerlendirilmektedir.

Bu nedenle, gelecekte enerji depolama sistemlerinin tasarımında, bu iki teknolojinin **tamamlayıcı nitelikte** kullanılması, sistem güvenilirliği ve enerji verimliliği açısından büyük avantaj sağlayacaktır.

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İKLİM DEĞİŞİKLİĞİNİN KÜMES HAYVANLARI ÜRETİMİ ÜZERİNE ETKİLERİ VE ÇÖZÜM ÖNERİLERİ

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ÖZET

İklim değişikliği son yıllarda, özellikle kurak ve yarı kurak iklimlerde kümes hayvanları üretimini olumsuz etkileyen önemli bir olgu olarak ortaya çıkmıştır. Son elli yılda kanatlı yetiştiriciliğinde yapılan genetik çalışmalarla üretim süresi kısalmış, hayvanların genetik potansiyeli, et ve yumurta verimi artmıştır. Kanatlı hayvanlara sunulan bakım, besleme, barınak ve çevre koşullarının da iyileştirilmesiyle genetik performansa ulaşmaları kolaylaşmıştır. Ancak son yıllarda yaşadığımız iklim krizi kantalı hayvanların ihtiyaç duydukları konfor alanını sunmayı zorlaştırmaktadır. Dengesiz yağışlar, su yetersizliği, yüksek nem ve çevre sıcaklıkları, piliçlerin gelişimi için elverişsiz bir ortam yaratmakta, iklim krizi nedeniyle tahıl üretiminde yaşanan düşüşler tahıl talebinde rekabet ve fiyatı artırmakta, yüksek yem maliyetleri kanatlı hayvan üretiminin sürdürülebilirliğinin olumsuz etkilemektedir. Bu derlemede iklim değişikliğinin kümes hayvanlarının performansı üzerine etkileri ve ısı stresine dayalı fizyolojik değişiklikler, ısı stresininin zararlı etkilerini iyileştirme veya azaltma stratejileri açısından genetik, yönetim ve besleme stratejileri irdelenmiştir. Isı toleransını iyileştirmek için erken ısı koşullandırma, kuluçkalık yumurtaların embriyonik yaşın bellirli bir döneminde yüksek sıcaklığa maruz bırakılması, alternatif kümes hayvan türlerinin kullanılması faydalı olabilir. Modern teknolojiler, genetik mühendislik ve sürdürülebilir tarım yöntemleri gibi çözümler, kümes hayvancılığı sektörünün iklim değişikliğine karşı dayanıklı hale gelmesini sağlayabilir. Eğitim ve bilinçlendirme faaliyetleri, üreticilerin iklim değişikliğine adapte olmasını kolaylaştıracak önemli bir adım olacaktır.

Anahtar kelimeler: İklim değişikliği, kümes hayvanları, ısı stresi, iyileştirme stratejileri

EFFECTS OF CLIMATE CHANGE ON POULTRY PRODUCTION AND SOLUTIONS

ABSTRACT

Climate change has emerged in recent years as a significant factor negatively impacting poultry production, particularly in arid and semiarid climates. Genetic researches which are conducted in poultry farming over the past fifty years has shortened production periods, increased the genetic potential of poultry production and as a result increase meat and egg yield. Improvements in care, feeding, housing, and environmental conditions have facilitated the achievement of genetic performance. However, the climate crisis we have experienced in recent years has made it difficult to provide the comfort zones required by poultry. Uneven rainfall, water scarcity, high humidity, and ambient temperatures create unfavorable conditions for poultry development. The decline in cereal production due to the climate crisis is increasing grain demand and prices, and high feed costs are negatively impacting the sustainability of poultry production. This review examines the effects of climate change on poultry performance, physiological changes related to heat stress, and genetic, management, and nutrition strategies to ameliorate or mitigate the harmful effects of heat stress. To improve heat tolerance, early heat conditioning, exposing hatching eggs to high temperatures during a certain embryonic period, and using alternative poultry breeds may be beneficial. Solutions such as modern technologies, genetic engineering, and sustainable agriculture methods can help the poultry sector become resilient to climate change. Education and awareness-raising activities will be an important step in facilitating producers adaptation to climate change.

Key words: climate change, poultry, heat stress, improvment strategies

Giriş

İklim değişikliği, dünya çapında çevresel, sosyal ve ekonomik değişimlere neden olan ciddi bir sorun olarak karşımıza çıkmaktadır. Giderek artan sıcaklıklar, anormal hava olayları ve su kaynaklarındaki azalma, ekosistemlerin dengesini bozmaktadır. Bu değişiklikler yalnızca doğal yaşamı değil, insan faaliyetlerini de derinden etkilemektedir. Özellikle tarım ve hayvancılık sektörü, iklim değişikliğinden doğrudan etkilenmektedir. Kümes hayvanları üretimi, dünya genelinde önemli bir gıda kaynağı olarak öne çıkarken, aynı zamanda küresel ısınma ve iklimsel değişikliklerin etkilerine de açıktır. Kümes hayvancılığı sektörü, gıda güvenliğinin sağlanmasında kritik bir rol oynarken, iklim değişikliği bu sektörün geleceğini tehdit etmektedir. Ancak, doğru stratejiler ve uygulamalarla bu tehditler minimize edilebilir.

Kümes hayvanları, gelişmekte olan birçok ülkenin ekonomisini canlandırmada, nitelikli hayvansal protein sağlamada ve özellikle kırsal alanlarda birçok kişinin geçimine katkıda bulunmada önemli bir rol oynamaktadır (Demeke 2004). Birleşmiş Milletler Gıda ve Tarım Örgütü'ne (FAO) göre, 2023 yılında yıllık kanatlı eti üretimi 142.5 milyon ton olarak gerçekleşmiş ve küresel et üretiminin %40.6' sına katkıda bulunmuştur. Kümes hayvanlarına yönelik artan talep, esas olarak tavuk etinin ana protein kaynağı olduğu gelişmekte olan ülkelerde gözlemlenmiş ve bu ülkeler daha varlıklı hale geldikçe bu talep de artmaya devam etmektedir (Speedy 2002). Kümes hayvanı eti ve yumurtasına yönelik artan talep, bunların tüketimine ilişkin dini tabuların bulunmamasından ve ayrıca fiyatlarının daha ucuz olmasından da kaynaklanmaktadır (Melesse2014).

Kümes hayvancılığı endüstrisi dünya çapında büyürken, özellikle sıcak ve nemli tropikal bölgelerde verimlilikleri üzerindeki en büyük kısıtlamanın ısı stresi olduğu kabul edilmektedir. Konfor/termin nötr bölgesi, yumurtlayan tavuklar için 19 ile 22 °C ve büyüyen piliçler için 18 ile 22 °C arasındadır (Charles 2002). Kanatlı hayvanlarda ısı stresi şu şekilde sınıflandırılır: akut: 27-38 °C 1-24 saat; orta: 27-38 °C 7 güne kadar; kronik veya şiddetli: 38-50 °C 7 gün veya daha fazla (Mujahid et al. 2007; Sohail et al. 2012; Vladimir et al. 2018). Kümes hayvanlarının sıcaklıkla ilişkili çevresel zorluklara, özellikle de ısı stresine karşı özellikle hassas olduğu görülmektedir. Modern kümes hayvanı genotiplerinin, daha yüksek metabolik aktiviteleri nedeniyle daha fazla vücut ısısı ürettiği öne sürülmüştür (Settar et al. 1999; Deeb, and Cahaner, 2002). Çevresel koşulların anlaşılması ve kontrol edilmesi, başarılı kümes hayvanı üretimi ve refahı için çok önemlidir.

İklim değişikliğinden kaynaklı yüsek sıcaklıklar kümes hayvanlarında büyüme, ölüm oranının artmasına, üremenin azalmasına, yumurta üretiminin, yumurta ve et kalitesinin düşmesine neden olur. Isı stresi, beyaz ve kırmızı kan hücrelerini azaltarak ve stres ve korku tepkilerini artırarak kümes hayvanlarının bağışıklık performansını düşürür. Örneğin, bazı araştırıcılar (McKechnie ve Wolf 2010; Rath et al. 2015) tarafından uzun süre ısı stresine maruz kalmanın kanatlılarda üretim kayıplarına ve aşırı durumlarda ölümlere neden olabileceği bildirilmiştir. Irshad ve arkadaşları (2012) kanatlı hayvanlarda ısı stresinin büyümede azalmaya, üremede düşüşe, yumurta üretiminde ve et kalitesinde azalmaya ve ölüm oranında artışa neden olduğunu bildirmişlerdir.

Bu çalışmada, iklim değişikliğinin kanatlı hayvan üretimi üzerindeki çeşitli olumsuz etkilerine genel bir bakış sağlamak ve bu olumsuz faktörün kanatlı hayvanlar üzerindeki etkilerini en aza indirmek için mevcut olan iyileştirme stratejilerini özetlemektir.

İklim değişikliğinin kümes hayvanı performansına etkisi

Küresel ısınmadan kaynaklı, ABD hayvancılık endüstrisinde tahmini toplam yıllık 1,69 ile 2,36 milyar dolarlık ekonomik kayba neden olmaktadır; bu toplamın 128 ile 165 milyon doları

kümes hayvancılığı endüstrisinde meydana gelmektedir (St-Pierre et al. 2003). Sohail ve ark (2012) göre, kronik ısı stresine maruz kalan piliçler 42 günlük yaşta önemli ölçüde azalmış yem alımına (%16,4), daha düşük vücut ağırlığına (%32,6) ve daha yüksek yem dönüşüm oranına (+%25,6) sahip olmuştur. Isı stresinin iki etlik pilic türü üzerindeki etkisini inceleyen Lu ve arkadaşları (2007), 21°C ile 34°C arasındaki sıcaklık derecesi artışı başına Arbor Acres piliçlerinde (ticari olarak hızlı büyüyen bir tür) yaklaşık %3,4 ve Beijing You'da (yerel olarak yavaş büyüyen bir tür) %1,7 oranında yem alımında azalma kaydetmiştir. Broylerlerin ısı stresine maruz kalması, göğüs ve but büyüklüğü gibi karkas özelliklerinde azalmaya neden olur (Lu ve ark. 2007). Isı stresi göğüs kaslarında protein ve kas içi yağ birikimini azaltır, bu da et kalitesini, besleyici değerini ve etin tadını düşürür (Zaboli ve ark. 2018).

Mashaly ve diğerlerine (2004) göre, ısı stresi yem alımını azaltmakta, besin kullanılabilirliğini etkilemekte, plazmadaki protein konsantrasyonunu düşürmekte ve tavukların daha küçük yumurtlamasına neden olmaktadır. 12 günlük sıcak stresi dönemi, günlük yem alımında azalmaya (28,58 g/tavuk) neden olarak yumurta üretiminde azalmaya (%28,8) yol açmıştır (Deng et al. 2012). Sıcağa maruz kalma aynı zamanda kalsiyum metabolizmasını da etkileyerek karbonik anhidraz ve kalsiyum bağlayıcı proteinin mRNA ekspresyonunu azaltır. Alkaloz ile birlikte yukarıda bahsedilen değişiklikler, plazma kalsiyum konsantrasyonunda azalmaya (Zhou ve ark. 1998; Mashaly ve ark. 2004), yumurta kabuğu kalınlığının azalmasına ve çatlak veya kırık yumurta sayısının artmasına neden olmaktadır (Ebeid ve ark. 2012). Star ve arkadaşları (2009) sıcak stresine maruz bırakılan yumurtacı tavuklarda yemden yararlanmada %31,6, yumurta üretiminde %36,4 ve yumurta ağırlığında %3,41 azalma olduğunu bildirmiştir. Başka bir çalışmada, ısı stresi üretim performansının düşmesinin yanı sıra yumurta kabuğu kalınlığının azalmasına ve yumurta kırılmasının artmasına neden olmuştur. Ebeid ve ark. (2012) göre, sıcaklık stresi yumurta ağırlığında (%3,24), yumurta kabuğu kalınlığında (%1,2), yumurta kabuğu ağırlığında (%9,93) ve yumurta kabuğu yüzdesinde (%0,66) önemli bir azalmaya yol açmıştır. Okonkwo ve Ahaotu (2019), çevre sıcaklığının 31,6°C'den 37,9°C'ye yükselmesiyle tavuklarda yem tüketiminin 108,3 g/tavuk/gün'den 68,9 g/tavuk/gün'e düştüğünü ve yumurta üretiminin %6,4 oranında azaldığını bildirmiştir.

Kanatlı hayvanlarda ısı stresi ve bazı fizyolojik değişiklikler arasındaki ilişki

Isı stresi sırasında birçok endokrin değişken etkilenir, kandaki kortikosteroid seviyeleri tavuk üzerindeki çevresel stres seviyesini göstermek için kullanılan standart bir ölçüdür (Beuving ve Vonder 1978; Zaboli et al. 2018). Hipotalamik-hipofiz-adrenal eksen, çok sayıda glukokortikoid üreterek ısı stresine verilen tepkileri düzenler. Isı stresi sırasında daha yüksek glukokortikoid seviyesinin genellikle dolaşımdaki kan glukoz seviyelerinde bir artışı teşvik edeceği, ancak uzun süreli ısı stresine maruz kalma sırasında kan glukoz seviyesinin düştüğü bildirilmiştir. Ayrıca, ısı stresinin metabolik hormonları azalttığı ve heterofil/lenfosit oranını artırdığı bildirilmiştir. Kanatlı hayvanların ısı stresine maruz kalmasının hipotalamustaki gonadotropin salgılatıcı hormon (GnRH) puls jeneratörünün frekansını azalttığı ve hipofiz bezinden folikül uyarıcı hormon (FSH) ve lüteinizan hormon (LH) salgılanmasını bozduğu bildirilmiştir (Jeronen ve ark. 1978). Hester ve arkadaşları (1996), leghornlarda düşük GnRH ve LH seviyesinin, ısı stresi sırasında artan prolaktin seviyesi ile ilişkili olduğunu öne sürmüştür.

Kanatlı üretiminde ısı stresinin zararlı etkilerini iyileştirme/azalma stratejileri

Genetik stratejiler

İklim değişikliğine dayanıklı ve hastalıklara karşı dirençli kanatlı genotiplerinin yetiştirilmesi, sürdürülülebilirlik için önemlidir. Genetik mühendislik ve seleksiyon yöntemleri kullanılarak,

hayvanlar hem verimli hem de iklim değişikliğine dayanıklı hale getirilebilir. Çeşitli araştırmalar, iklim değişikliğiyle mücadele etmek için genetik çeşitliliğin artırılmasının önemini vurgulamaktadır (Deeb et al., 2017).

Kümes hayvanı ırkları arasında ısıya tolerans düzeylerinde farklılıklar olduğu bildirilmiştir (Mashaly ve ark. 2004; Melesse ve ark. 2011), bu da genetik modifikasyonu ısı stresini hafifletmek için potansiyel bir yöntem haline getirmektedir. Isı stresinin etkisini azaltan ve aynı zamanda cücelik için cinsiyete bağlı resesif geni hedef alan birkaç gen tanımlanmıştır (Vandana ve ark. 2021). Cücelik için cinsiyete bağlı resesif genin hedeflenmesi, tavukların vücut boyutunun küçülmesine neden olacaktır. Bu da metabolik ısı çıkışını azaltır ve tavukların göreceli yüzey alanını artırarak ısı dengesinin sağlanmasını kolaylaştırır (Deeb ve ark. 1993). Kümes hayvanlarının markör destekli seçici ıslahında, HSP genlerindeki polimorfizmler, cüce geni, frizzle geni ve çıplak boyun genleri, üstün termotoleransa sahip bir ırk geliştirmek için kullanılabilecek önemli termo-tolerans genlerinden bazılarıdır (Yu et al. 2008; Chen et al. 2013).

Yönetim stratejileri

İklim değişikliğinin kümes hayvanları üzerindeki zararlı etkisini hafifletmeye yönelik yönetim stratejileri arasında yeterli hayvan yoğunluğu, uygun barınak, gölgelik, havalandırma, serin içme suyu ve yağmurlama sistemlerinin sağlanması yer almaktadır. Yüksek hayvan yoğunluğu kalabalıkla ilişkilidir ve sürü içinde yüksek enerji üretimine yol açar.

Havalandırma sadece oksijen, karbondioksit, amonyak ve nem açısından uygun hava kalitesini korumak için değil, aynı zamanda sıcak koşullarda konvektif ısı kaybı için yeterli hava hareketi sağlamak üzere kümes içinde uygun hava hareketini sağlamak için de önemlidir (Butcher ve Miles 2012). Kümes çevresindeki çim örtüsü, kümes çevresindeki ağaç dikimine benzer şekilde, kanatlılar üzerindeki ısı yükünü azaltmanın bir yoludur (Saeed ve ark. 2019). Fanlarla birlikte çalışan fıskiyelerin eklenmesi buharlaşmalı soğutmayı artırabilir (Daghir 2008b). Yüksek sıcaklıklar ve uzun süreli sıcak hava dalgaları nedeniyle tavuk çiftliklerinde en uygun koşulları sağlamak için havalandırma, soğutma sistemleri ve yapay aydınlatma gibi tüm çevre koşullarının denetim altında olduğu çevre kontrollü kümeslerde elektrik tüketimi de artmaktadır. Bunun sonucunda, enerji maliyetleri arttarken elde edilen ürünün de maliyeti artmaktadır.

Günün daha serin saatlerinde yemleme, kanatlıların üretim verimliliğini artırabilir ve bu yöntemler ısı stresinin olumsuz etkilerini hafifletmek için ekonomiktir (Das ve ark. 2014). Isı stresi döneminde yem kısıtlaması, günün en yoğun saatlerinde metabolik ısı üretimini azaltmanın bir başka yoludur. Sıcak stresi sırasında %60 yem kısıtlamasına maruz kalan civcivlerin büyüme performansının arttığı ve ölüm oranının azaldığı bildirilmiştir (Lin ve ark. 2006).

Beslenme stratejileri

Beslenme müdahalesi, ısı stresinin etkilerini iyileştirmeye yardımcı olmak ve kümes hayvanlarının üretkenlik performansını artırmak için umut verici bir yöntemdir. Örneğin, 31°C'de yağ ilavesi (%5) yumurta tavuklarında yem alımını yaklaşık %17 artırırken, 10-18°C'de yem alımını sadece %4,5 artırmıştır (Daghir 2008c). Broylerler için 1,5:1 ve yumurtacı tavuklar için 1:1 oranında yeme su eklenmesi, sıcak stresi sırasında kanatlıların performansı üzerinde olumlu bir etkiye sahip olmuştur (Kutlu ve Forbes 1993). Yemin ufalanması ve daha küçük yem partikül boyutu sağlanması, sindirimde taşlığın işini azaltır ve metabolik ısı üretimini azaltmaya yardımcı olur (Amerah ve ark. 2007).

Erken ısı koşullandırma ve maternal epigenetik yöntemler

Erken ısı koşullandırma, kanatlıların, özellikle de piliçlerin ısı toleransını iyileştirmek için umut verici bir yöntemdir. Bu yöntem, civcivlerin çok genç yaşta (24 saat ile 5 gün) yüksek sıcaklığa (36-38 °C) maruz bırakılmasını içerir (**Lin ve ark. 2006**). Maternal epigenetik, damızlık tavukları yüksek sıcaklığa alıştırmak için yüksek sıcaklığa maruz bırakmayı içerir. Ebeveynler daha sonra ısıya dayanıklı genleri yavrularına aktaracaktır.

Kuluçka yönetimi

Kuluçkalık yumurtaların embriyonik yaşın belirli bir döneminde yüksek kuluçka sıcaklığına maruz bırakılmasını içerir. Bu, HPA (hipotalamus-pituiter-adrenal) ekseninin ısıya maruz kalmaya dayanacak kadar geliştiği dönemde yapılır. Bu, HPA ekseninin aktivasyonunu ve HSP (ısı şok protein)'nin ekspresyonunu etkileyen hormonal ve genetik değişikliklere neden olur. Tavuklar yetiştirme dönemi boyunca, kuluçka sırasında yaşanan ısı stresi etkisi nedeniyle çevresel uyaranlardaki değişikliklerle başa çıkabilecektir.

Alternatif kümes hayvanları

Bıldırcın, ördek ve kaz gibi ısı stresine karşı yüksek direnç gösteren diğer alternatif kümes hayvanı türlerinin üretimi, sürdürülebilir kümes hayvanı üretimi ve gıda arzının sürdürülmesinde kümes hayvanı türlerinin toplam katkısının iyileştirilmesine yardımcı olabilir. Bıldırcınlar, ördekler ve kazlar yarı yabani kümes hayvanlarıdır ve ticari etlik piliçler ve yumurtacı tavuklar gibi yüksek performans için genetik olarak seçilmemiş ve geliştirilmemiştir. Bu durum, bu kümes hayvanlarına ısı stresine karşı ticari etlik piliç ve yumurta tavuklarından daha yüksek direnç kazandırmaktadır.

Sonuç

İklim değişikliği, kümes hayvanları üretimini ciddi şekilde etkilemektedir. Yüksek sıcaklıklar, su kaynaklarındaki azalma, yem üretimindeki verimlilik kayıpları ve hastalıklar, sektördeki verimliliği düşürmektedir. Ancak, uygun önlemler alındığında bu etkiler en aza indirilebilir. Modern teknolojiler, genetik mühendislik ve sürdürülebilir tarım yöntemleri gibi çözümler, kümes hayvancılığı sektörünün iklim değişikliğine karşı dayanıklı hale gelmesini sağlayabilir. Eğitim ve bilinçlendirme faaliyetleri, üreticilerin iklim değişikliğine adapte olmasını kolaylaştıracak önemli bir adım olacaktır.

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SİRKELERİN BİYOLOJİK AKTİVİTELERİ

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ÖZET

Sirke (acetous fermentasyon ürünü), gıdalarda yaygın olarak kullanılan ve tarihsel olarak hem tatlandırıcı/koruyucu hem de geleneksel tıpta çeşitli amaçlarla kullanılan dünya çapında asidik bir çeşnidir. Sirke, sıvı hal ve katı hal fermantasyon teknikleriyle demlenen çeşitli besin maddeleri ve biyoaktif bileşenler içerir. Sirkeye özgü asetik asit, organik asitler, polifenoller, flavonoidler, melanoidinler, organik bileşikler ve diğer biyoaktif maddeler içerdiği için biyolojik aktiviteleri araştırma konusu olmuştur. Bu besin maddeleri; enerji üretimi, hücre metabolizmasının düzenlenmesi, bağışıklık sisteminin modülasyonu, antioksidan savunma, antikoagülan etki ve beyin gelişiminin desteklenmesi gibi çeşitli biyolojik işlevlerde rol oynamaktadır. Ayrıca, sirkede bulunan organik asitler, polifenoller, melanoidinler ve tetrametilpirazin gibi biyoaktif bileşenler; antioksidan etki göstermenin yanı sıra lipid metabolizmasını düzenleme, karaciğer fonksiyonlarını koruma, kan basıncı ve glikoz düzeylerini dengeleme, yorgunluğu azaltma ve tümör gelişimini baskılama gibi faydalar sunmaktadır. Bununla birlikte, sirkede yer alan yeni fonksiyonel bileşenlerin tanımlanması ve bu bileşiklerin sağlık üzerindeki etkilerinin moleküler mekanizmalarının aydınlatılması için ileri araştırmalara ihtiyaç duyulmaktadır. Bu çalışmada amaç, sirkelerin antioksidan, antimikrobiyal, antidiabetik, antihipertansif, antitümör/anticarcinogenik ve diğer biyolojik aktivitelerini literatürden örneklerle sunmak; bu çalışmaların sonuçlarını tablolarla göstermek ve geleceğe yönelik araştırma önerileri sunmaktır.

Anahtar Kelimeler: sirke, biyolojik aktivite, biyoaktif bileşenler

BIOLOGICAL ACTIVITIES OF VINEGARS

ABSTRACT

Vinegar (an acetous fermentation product) is an acidic condiment widely used in foods and historically employed both as a flavoring/preserving agent and for various purposes in traditional medicine around the world. Vinegar contains a variety of nutrients and bioactive compounds produced through liquid- and solid-state fermentation techniques. Due to its composition—acetic acid, organic acids, polyphenols, flavonoids, melanoidins, organic compounds, and other bioactive substances—vinegar has become a subject of extensive biological activity research. These nutrients play important roles in several biological functions, including energy production, regulation of cellular metabolism, modulation of the immune system, antioxidant defense, anticoagulant activity, and support of brain development. Moreover, bioactive compounds found in vinegar, such as organic acids, polyphenols, melanoidins, and tetramethylpyrazine, provide various health benefits including antioxidant effects, regulation of lipid metabolism, protection of liver functions, control of blood pressure and glucose levels, reduction of fatigue, and inhibition of tumor development. However, further studies are needed to identify new functional components present in vinegar and to elucidate the molecular mechanisms underlying their health-promoting effects. The aim of this study is to present examples from the literature regarding the antioxidant, antimicrobial, antidiabetic, antihypertensive, antitumor/anticarcinogenic, and other biological activities of vinegars, to summarize the findings of these studies in tables, and to propose future research directions.

Keywords: vinegar, biological activity, bioactive compounds

GİRİŞ

Sirke, tarih boyunca hem bir gıda bileşeni hem de kültürel bir unsur olarak önemli bir yere sahip olan, temel olarak etanolün asetik asite oksidasyonu sonucu elde edilen asidik bir fermantasyon ürünüdür. Bilinen en eski fermantasyon ürünlerinden biri olan sirke, insanlık tarihi boyunca yalnızca bir lezzet artırıcı ve koruyucu ajan olarak değil, aynı zamanda sağlık amaçlı kullanımıyla da dikkat çekmiştir. Antik Mezopotamya'dan Roma uygarlığına, Doğu Asya toplumlarından günümüzdeki modern gıda endüstrisine kadar geniş bir süreklilik içinde sirke üretimi ve tüketimi varlığını sürdürmüştür (Solieri & Giudici, 2009).

Sirke üretimi, iki temel biyolojik sürece dayanır: (i) alkolik fermantasyon, (ii) asetik fermantasyon. Birinci aşamada mayalar tarafından şekerler etanole dönüştürülürken, ikinci aşamada Acetobacter ve Gluconobacter türü asetik asit bakterileri etil alkolü oksitleyerek asetik asit oluşturur. Ortaya çıkan nihai ürün, yalnızca asetik asit değil, aynı zamanda polifenoller, organik asitler, uçucu bileşenler, mineraller ve biyoaktif metabolitler açısından da zengindir (Budak & Güzel-Seydim, 2010).

Günümüzde sirke, geleneksel üretim yöntemlerinin yanı sıra modern teknolojilerle standardize edilen süreçler aracılığıyla da elde edilmektedir. Yüzey (Orleans yöntemi) ve daldırma sistemleri (Frings acetator gibi) arasında verim, süre ve aroma bileşenleri bakımından belirgin farklar bulunmaktadır. Üretim tekniği, sirkenin duyusal özellikleri kadar kimyasal bileşimini ve biyolojik aktivitesini de doğrudan etkilemektedir (Oztürk & Polat, 2019).

Gıda bilimi ve beslenme alanında sirkenin artan araştırma ilgisi, onun fonksiyonel gıda bileşeni olma potansiyelinden kaynaklanmaktadır. Çeşitli çalışmalar sirkenin antimikrobiyal, antioksidan, antiinflamatuar, glisemik kontrolü destekleyici ve lipid metabolizmasını düzenleyici etkilere sahip olabileceğini bildirmiştir (Johnston & Gaas, 2006). Bu etkilerin önemli bir kısmı asetik asit konsantrasyonu, fenolik bileşen profili ve fermantasyon sürecindeki mikrobiyal aktivite ile ilişkilidir.

Elma sirkesi, üzüm sirkesi, nar sirkesi, hurma sirkesi ve pirinç sirkesi gibi çeşitler coğrafi bölgelere göre farklı hammaddelerden üretilmekte olup, bu çeşitlilik kimyasal kompozisyonun ve sağlık üzerindeki etkilerin de farklılaşmasına neden olmaktadır. Sirke çeşitleri üzerine yapılan karşılaştırmalı analizler, özellikle fenolik madde içeriği ve oksidatif stabilite açısından belirgin değişkenlikler olduğunu göstermektedir (Mas et al., 2014).

Sonuç olarak sirke, hem üretim teknolojileri hem de biyoaktif özellikleri bakımından oldukça zengin bir araştırma alanı sunmaktadır. Güncel literatür, sirkenin yalnızca geleneksel bir gıda bileşeni olmadığını, aynı zamanda potansiyel bir fonksiyonel gıda ve sağlık destekleyici ajan olarak da değerlendirilmesi gerektiğini ortaya koymaktadır.

Sirkelerin Antioksidan Aktiviteleri

Bakır S. Ve ark. (2017), Türkiye'nin farklı şehirlerinden temin edilen 18 adet ev yapımı "incir sirkeleri" nin fizikokimyasal, fenolik / flavonoid içerikleri ile antioksidan ve antimikrobiyal özelliklerini incelemişlerdir. Toplam fenolik ve flavonoid içerikleri; ayrıca $ABTS^{+}$ ve DPPH radikal süpürme aktiviteleri incelemişlerdir. Sirkelerin toplam antioksidan kapasiteleri (TAC), dört farklı in vitro yöntem olan ABTS, CUPRAC, DPPH ve FRAP testleri kullanılarak eş zamanlı olarak değerlendirilmiştir. Yapılan analizler, özellikle balzamik sirkenin diğer örneklerle karşılaştırıldığında en yüksek toplam flavonoid içeriğine (TFC: 96 ± 18 mg CE/100 mL) ve toplam fenolik içeriğe (TPC: 255 ± 24 mg GAE/100 mL) sahip olduğunu ortaya koymuştur. Ayrıca, toplam antioksidan kapasitenin en yüksek olduğu değerler CUPRAC (709 ± 108 mg Trolox/100 mL) ve FRAP (421 ± 28 mg Trolox/100 mL) yöntemleriyle belirlenmiş;

bu sonuçlar balzamik sirkenin antioksidan potansiyelinin diğer sirke türlerine kıyasla belirgin derecede üstün olduğunu göstermiştir.

Öztürk S. ve ark. (2023), yaptıkları çalışmada *Saccharomyces cerevisiae* ile alkol fermantasyonu ve dört farklı sirke başlatıcısı (üzüm, elma, alkol sirkesi ve üzüm-elma sirkesi karışımı) ile asetik asit fermantasyonunun siyah havuç suyunun (SHS) bazı fizikokimyasal özellikleri (pH, toplam asitlik, toplam kuru madde, indirgen şeker, toplam fenolik ve antioksidan aktivite) üzerine etkisi araştırılmışlardır. SHS'nin siyah havuç şarabına işlenmesinin toplam fenolik içerikte yalnızca %4'lük bir genel azalmaya yol açtığını ve asetifikasyon işlemi nedeniyle siyah havuç sirkelerinde toplam fenolik içerikte %21-32'lik bir azalmanın daha hacim-ağırlık bazında (mg/L) gözlemlendiğini göstermişlerdir. Sirke üretim süreci boyunca antioksidan aktivite için de benzer bir azalma eğilimi belirlemişlerdir. Toplam fenolik içerik, tohum sirkelerinden herhangi biriyle aşılamadan etkilenmediğini raporlamışlardır. Piyasadaki muadillerinden daha iyi biyoaktif özellikler sergilediğini ve siyah havuçtan, önemli miktarda nutrasötik bileşeni korunarak sirke başarıyla üretmişlerdir.

Öztürk İ. ve ark. (2015), Türkiye'nin farklı bölgelerinden toplanan yirmi geleneksel ev yapımı sirke, antioksidan, antimikrobiyal, mineral ve uçucu profilleri ile fizikokimyasal ve antimikrobiyal özellikleri ve mikrobiyotaları açısından karakterize etmişler ve sirkeleri karakterize edilen özelliklerine göre beş endüstriyel sirke ile karşılaştırmışlardır. Tüm sirkelerin fizikokimyasal özellikleri son derece değişken olduğunu belirtmişleridr. Geleneksel sirkelerde toplam 61 uçucu bileşik belirlemişlerdir. Bazı geleneksel sirkelerde en bol bulunan bileşikler ise α-terpineol ve etil asetat ve sirkelerde tespit edilen yaygın bileşik fenetil alkol olduğunu raporlamışlardır.

Aydın, S., ve Demir Gökışık, C. (2019), yaptıkları çalışmada *Vitis vinifera'* dan elde edilen sirkenin antioksidan aktivitesini (Toplam fenolik içerik, toplam flavonoid içeriği, CUPRAC aktivitesi, DPPH ve ABTS radikal temizleme aktivitesi) belirlemişlerdir. Toplam fenolik içerik 160,23 ± 0,007 µg GAE/ml, toplam flavonoid içeriği 298 ± 0,069 µg CE/ml, toplam antioksidan kapasitesi 113,12 ± 0,011 µg AAE/ml olarak tespit etmişlerdir. Sirkenin CUPRAC aktivitesi ve DPPH radikal temizleme aktivitesi standartlardan daha yüksek bulmuşlardır. Üzüm sirkesi, standartlardan daha düşük ABTS radikal temizleme aktivitesi göstermişlerdir. Üzüm sirkesi ve standartların (BHT ve Rutin) hem ABTS hem de DPPH radikal temizleme aktivitesi, artan konsantrasyonla birlikte arttığını belirtmişlerdir. Sirkenin ABTS aktivitesi %27,47 ile %63,72 arasında değiştiğini belirtmişlerdir. Bu çalışma, üzüm sirkesinin önemli antioksidan özelliklere sahip olduğunu ve sentetik antioksidan ajanlara alternatif olabileceğini raporlamışlardır.

Jia K. ve ark. (2024), yaptıkları çalışmada antioksidan kapasite, DPPH, hidroksil ve süperoksit anyon radikal süpürücü analizleri ile değerlendirmişlerdir. Sirke özütünde, DPPH, hidroksil ve süperoksit anyon radikalleri için sırasıyla %71, %82,2 ve %81,3'lük maksimum süpürücü oranlarla önemli bir antioksidan potansiyel olduğunu raporlamışlardır.

Karadağ A., ve ark. (2020), yaptıkları çalışmada bütün meyveleri herhangi bir koruyucu madde kullanılmadan geleneksel yöntemle on iki sirke üretip, örneklerin fizikokimyasal özellikleri, toplam fenolik içerik (TPC), toplam flavonoid içerik (TFC), fenolik bileşik profilleri, antioksidan aktiviteleri (DPPH• süpürücü aktivite, FRAP, CUPRAC) ve uçucu bileşimleri ile mayonezde oksidasyonu geciktirme yetenekleri açısından karakterize ettiklerini bildirmişlerdir. Tüm sirke örneklerinde başlıca fenolik asitler olarak **gallik asit**, **protokateşuik asit** ve **kafeik asit** belirlemişler, ayrıca flavonoidlerin arasında **rutin** ve **kaempferol** tespit etmişlerdir. Uçucu bileşikler içinde asetik asit esterleri ve alkoller baskın olup, tüm örneklerde farklı düzeylerde **izoamil asetat** saptadıklarını beyan etmişlerdir. Sirkelerin **DPPH radikali**

giderme kapasitesi ile bu sirkelerle hazırlanan mayonezlerin **OXITEST indüksiyon periyodu** arasında güçlü bir pozitif korelasyon ($r > 0,70$) bulmuşlardır. Sirke türü mayonezin **oksidatif stabilitesini anlamlı şekilde etkilediğini beyan etmişlerdir** ($p < 0,05$). Ayrıca ana bileşen ve kümeleme analizleri, sirke örneklerinin kimyasal profillerine göre net biçimde ayrılabildiğini göstermiştir. Bu bulgular, meyve tipinin sirkenin duyusal özellikleri yanında **fizikokimyasal ve biyoaktif niteliklerini** de belirleyen kritik bir üretim faktörü olduğunu ortaya koyduğunu beyan etmişlerdir.

Bu çalışmaların çoğu, sirkelerin sadece asetik asit içerdiğini değil; fenolik bileşikler, flavonoidler, uçucu bileşikler, vb. biyolojik aktif bileşenler içerdiğini gösteriyor bu da sirkeyi "fonksiyonel gıda / sağlık destekleyici gıda" olarak değerlendirilmesi gerektiğini göstermektedir. Farklı hammaddeler (üzüm, kara havuç, alıç, incir, persimon vb.) ve farklı üretim yöntemlerinin (geleneksel, endüstriyel, meyve çeşidi, konsantre su vb.) antioksidan kapasiteyi önemli ölçüde değiştirdiğini göstermektedir. Çok sayıda antioksidan kapasite testi uygulanması DPPH, ABTS, CUPRAC, FRAP gibi sonuçların daha güvenilir ve karşılaştırılabilir olmasını sağlamıştır.

Sirkelerin Antimikrobiyal Aktiviteleri

Bakır S. Ve ark. (2017), Türkiye'nin farklı şehirlerinden temin edilen 18 adet ev yapımı "incir sirkeleri" nin fizikokimyasal, fenolik / flavonoid içerikleri ile antioksidan ve antimikrobiyal özelliklerini incelemişlerdir. Yapılan çalışmada farklı sirkelerin *Staphylococcus aureus, Salmonella Typhimurium* ve *Escherichia coli*' ye karşı antimikrobiyal aktiviteleri disk difüzyon yöntemi kullanılarak değerlendirilmişlerdir. Balzamik sirkenin yine en yüksek antimikrobiyal aktiviteye sahip örnek olduğu belirlendi ve *S. Typhimurium*' a karşı güçlü bir antibakteriyel aktivite gösterdiğini raporlamışlardır.

Öztürk İ. ve ark. (2015), Türkiye'nin farklı bölgelerinden toplanan yirmi geleneksel ev yapımı sirke, antioksidan, antimikrobiyal, mineral ve uçucu profilleri ile fizikokimyasal ve antimikrobiyal özellikleri ve mikrobiyotaları açısından karakterize etmişler ve sirkeleri karakterize edilen özelliklerine göre beş endüstriyel sirke ile karşılaştırmışlardır. Endüstriyel sirkeler yüksek miktarda antimikrobiyal aktivite gösterirken, sadece üç geleneksel sirke tüm test mikroorganizmaları için antimikrobiyal aktiviteye sahip olduğunu söylemişlerdir. Bu sonuçlara göre, geleneksel sirkeler genellikle yüksek mikrobiyal yüke sahipti; fakat endüstriyel sirkelerde nadiren tespit etmişlerdir.

Jia K. ve ark. (2024), yaptıkları çalışmada *Staphylococcus aureus, Salmonella, Saccharomyces cerevisiae* ve *Bacillus subtilis*' e karşı disk difüzyon testi ile değerlendirilmişlerdir. Alıç sirkesinin test edilen tüm mikroorganizmalara karşı inhibitör etki gösterdiğini ve en güçlü aktivitenin *Salmonella*' ya karşı olduğunu raporlamışlardır.

Aydın R. (2013), yaptıkları araştırmada, Uzundere'de ve İspir'de üretimi yapılan dut (*Morus alba*) sirkesinin antimikrobiyal etkisi ve antioksidan özellikleri incelenmiştir. Antimikrobiyal özellikleri 8 farklı bakteri ve 1 adet fungustan oluşan test mikroorganizmaları (*S. aureus, Streptococcus pyogenes, Klebsiella oxytoca, Enterococcus faecalis, Bacillus cereus, Bacillus subtilis, Erwinia carotovora, E. coli, Candida albicans*) kullanılmışlardır. Çalışmada test edilen tüm mikroorganizmaların dut sirkesine karşı farklı derecelerde duyarlı oldukları tespit edilmiştir. Disk difüzyon yöntemine göre duyarlılık sıralamasının en yüksekten en düşüğe doğru şu şekilde olduğu gözlemlenmişlerdir: *S. aureus* (28 mm), *K. oxytoca* (24,6 mm), *B. subtilis* (23,3 mm), *S. pyogenes* (20,6 mm), *E. faecalis* (19,6 mm), *B. cereus* (15,3 mm), *E. carotovora* (13 mm), *C.albicans* (9,6 mm) ve *E.coli* (5,3 mm) olduğunu raporlamışlardır.

Koç İ., ve ark. (2018), tarafından gerçekleştirilen çalışmada, fındık kabuklarından elde edilen odun sirkesinin *Aspergillus niger* ve *Penicillium digitatum* üzerindeki antifungal etkisi in vitro koşullarda değerlendirilmiştir. Odun sirkesi %1, %3, %5, %7 ve %10 olmak üzere farklı konsantrasyonlarda hazırlanmış ve test etmişlerdir. Elde edilen bulgular, odun sirkesi konsantrasyonu arttıkça antifungal etkinin de belirgin şekilde yükseldiğini göstermişlerdir. Ayrıca odun sirkesinin her iki fungus türünde de misel gelişimini anlamlı düzeyde inhibe ettiği belirtmişlerdir.

Sirkenin Antikanser Aktivitesi

Kaya M.M., ve ark. (2021), çalışmanın bulgularına göre ticari sirke, ev yapımı sirkeye kıyasla daha belirgin bir antiproliferatif etki gösterdiğini belirtmişlerdir. Bununla birlikte, tüm doğal (nötralize edilmemiş) sirke örnekleri, nötralize edilmiş olanlara göre daha güçlü antiproliferatif aktivite sergilediğini raporlamışlardır. Dikkat çekici bir şekilde, ev yapımı sirkelerin hem doğal hem de nötralize edilmiş formlarında %6,25–%1,56 konsantrasyon aralığında hücre canlılığında artış gözlenmişlerdir. Genel olarak değerlendirildiğinde, elma sirkesi miyelom hücreleri üzerinde anlamlı düzeyde antiproliferatif etki oluşturduğunu raporlamışlardır.

Mohammed N.E. ve ark. (2019), yaptıkları araştırmada dondurularak kurutulmuş ananas sirkesinin in vitro apoptoz ve metastaz inhibe edici potansiyeli, MTT, hücre döngüsü analizi, Annexin V testi ve çizik (wound-healing) analizi kullanılarak değerlendirmişlerdir. Çalışmanın in vivo kısmında ise 4T1 hücreleriyle tümör oluşturmuşlar, BALB/c fareleri kullanılmış; bu farelere 28 gün boyunca vücut ağırlıklarına göre 0,08 mL/kg veya 2 mL/kg taze hazırlanmış ananas sirkesi uygulanarak etkiler detaylı bir şekilde incelemişlerdir. Sonuçlara göre in vitro analizlerde, 48 saatlik uygulama sonrasında ananas sirkesi için IC_{50} değeri 0,25 mg/mL olarak belirlenmişlerdir. Annexin V/PI ve çizik kapatma testlerinin sonuçları, ananas sirkesinin hücre popülasyonunun yaklaşık %70'inde apoptozu indüklediğini ve 4T1 hücrelerinde yara iyileşmesini (hücre göçünü) %30 oranında engellediğini ortaya koymuşlardır. İn vivo deneylerde ise yüksek konsantrasyonda uygulanan ananas sirkesi (2 mL/kg), tedavi edilmeyen 4T1 tümörlü farelerle karşılaştırıldığında tümör ağırlığı ve hacminde yaklaşık %45'lik bir azalma sağladığını raporlamışlardır.

Sonuç

Bu derleme kapsamında incelenen çalışmalar, sirkelerin yalnızca geleneksel bir gıda ürünü olmanın ötesinde, biyolojik açıdan çok yönlü bir etki profiline sahip olduğunu açıkça göstermektedir. Sirke, içerdiği asetik asit, fenolik bileşikler, flavonoidler, organik asitler ve bazı uçucu bileşenler sayesinde geniş bir yelpazede antioksidan, antimikrobiyal, antifungal ve antiproliferatif aktivite sergilemektedir. Antioksidan kapasiteyi belirlemeye yönelik analizlerde (ABTS, DPPH, CUPRAC, FRAP), özellikle balzamik ve bazı meyve sirkelerinin yüksek fenolik içeriğe bağlı olarak güçlü radikal temizleme potansiyeline sahip olduğu görülmektedir.

Antimikrobiyal ve antifungal çalışmalar, sirkenin hem bakteri hem de küf türlerine karşı etkili olduğunu; bu etkinin çoğunlukla pH düşürücü özellik, hücre membranı bütünlüğünün bozulması ve fenolik bileşiklerin sinerjik katkısıyla ortaya çıktığını göstermektedir. Fındık kabuğu odun sirkesi gibi bazı özel sirke türlerinin ise belirli funguslar üzerinde misel gelişimini anlamlı derecede inhibe ettiği raporlanmıştır.

Son yıllarda artan sayıda çalışma, sirkenin antikanser potansiyeli üzerinde de durmakta; çeşitli sirke türlerinin kanser hücrelerinde proliferasyonun baskılanması, apoptozun indüklenmesi, hücre döngüsü durdurulması ve hücre göçünün/metastazın engellenmesi gibi önemli biyolojik etkiler gösterebileceğini ortaya koymaktadır. Ananas, elma ve alıç gibi meyvelerden üretilen

sirkelerin özellikle yüksek fenolik içeriği ve antioksidan kapasitesi nedeniyle kanser hücreleri üzerinde anlamlı seviyede antiproliferatif etki oluşturduğu bildirilmiştir.

Genel olarak değerlendirildiğinde, sirkenin biyoaktif etkileri; hammadde tipine, fermantasyon koşullarına, fenolik kompozisyona, asitlik düzeyine ve işleme yöntemlerine bağlı olarak önemli ölçüde değişkenlik göstermektedir. Bununla birlikte, mevcut veriler sirkenin fonksiyonel gıda olarak taşıdığı potansiyeli güçlü şekilde desteklemektedir. Yine de, bu bulguların klinik uygulamalara uyarlanabilmesi için daha kapsamlı in vivo ve özellikle insan odaklı çalışmaların yapılmasına ihtiyaç bulunmaktadır. Sirkenin çok yönlü biyolojik aktiviteleri, onu hem gıda bilimi hem de sağlık bilimleri açısından dikkate değer bir araştırma alanı hâline getirmektedir.

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SİVAS'IN DEĞİŞEN İKLİM KOŞULLARINDA BAZI EKMEKLİK BUĞDAY GENOTİPLERİNİN MORFOLOJİK UYUM YETENEKLERİNİN BELİRLENMESİ

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Özet
Bu çalışma, Orta Anadolu'nun tipik karasal iklim özelliklerine sahip Sivas ekolojik koşullarında yetiştirilen 40 ekmeklik buğday (*Triticum aestivum* L.) genotipinin morfolojik ve verim unsurları bakımından performanslarının değerlendirilmesini amaçlamaktadır. Araştırmada bitki boyu (cm), başak uzunluğu (cm), başakta tane sayısı (adet), başakta tane ağırlığı (g), bin tane ağırlığı (g) ve tane verimi (kg/da) gibi temel agronomik özellikler incelenmiştir. Elde edilen sonuçlar, genotipler arasında incelenen tüm özellikler bakımından istatistiksel olarak anlamlı farklılıkların bulunduğunu göstermiştir. Özellikle tane verimi ile bin tane ağırlığı, başakta tane sayısı ve başakta tane ağırlığı arasında pozitif yönlü ilişkiler tespit edilmiş olup, bu durum söz konusu özelliklerin Sivas'ın değişken iklim koşullarında verim oluşumunda belirleyici rol oynadığını ortaya koymuştur. Ana bileşen analizi ve kümeleme analizleri, genotipler arasında verim ve morfolojik özellikler bakımından geniş bir varyasyon bulunduğunu ve genetik çeşitliliğin yüksek olduğunu göstermiştir. Bununla birlikte, bazı genotiplerin kuraklık ve sıcaklık stresinin belirgin olduğu yetiştirme dönemlerinde dahi stabil performans sergilemesi, bu genotiplerin bölge koşullarına yüksek adaptasyon yeteneğine sahip olduğunu ortaya koymaktadır. Sonuç olarak, çalışma kapsamında değerlendirilen ekmeklik buğday genotipleri arasında hem yüksek tane verimi hem de üstün adaptasyon kapasitesi sergileyen hatlar belirlenmiş olup, bu genotiplerin Sivas ve benzeri ekolojik bölgelerde yürütülecek buğday ıslah programlarında değerli çeşit adayı materyaller olarak kullanılabileceği düşünülmektedir. Araştırma bulguları, iklim değişikliğine bağlı olarak artan çevresel stres koşullarında bölgeye uyumlu, yüksek verimli buğday çeşitlerinin geliştirilmesine önemli katkılar sunmaktadır.
Anahtar Kelimeler: Ekmeklik buğday (*Triticum aestivum* L.), Adaptasyon, Tane verimi, Orta Anadolu, Morfolojik özellikler

ASSESSMENT OF MORPHOLOGICAL ADAPTATION TRAITS OF SELECTED BREAD WHEAT GENOTYPES UNDER CHANGING CLIMATIC CONDITIONS IN SİVAS

Abstract

This study aimed to evaluate the performance of 40 bread wheat (*Triticum aestivum* L.) genotypes grown under the ecological conditions of Sivas, which represent the typical continental climate of Central Anatolia, in terms of morphological and yield-related traits. The investigated agronomic parameters included plant height (cm), spike length (cm), number of grains per spike, grain weight per spike (g), thousand kernel weight (g), and grain yield (kg da^{-1}). The results revealed statistically significant differences among genotypes for all examined traits. Notably, positive relationships were detected between grain yield and thousand kernel weight, number of grains per spike, and grain weight per spike, indicating that these traits play a decisive role in yield formation under the variable climatic conditions of Sivas. Principal component analysis and cluster analysis further demonstrated a wide range of variation among genotypes, reflecting a high level of genetic diversity in terms of yield components and morphological characteristics. Moreover, some genotypes exhibited stable performance even under pronounced drought and heat stress conditions, highlighting their superior adaptability to the regional environment. In conclusion, several bread wheat genotypes with both high grain yield and strong adaptation capacity were identified in this study. These genotypes may serve as valuable candidate materials for wheat breeding programs conducted in Sivas and similar agro-ecological regions. The findings provide important insights for the development of regionally adapted, high-yielding bread wheat cultivars under increasing environmental stress conditions associated with climate change.

Keywords: Bread wheat (*Triticum aestivum* L.), Adaptation, Grain yield, Central Anatolia, Morphological traits

1. Giriş

Dünya nüfusundaki artışa paralel olarak güvenilir ve sürdürülebilir gıda kaynaklarının temini, küresel ölçekte stratejik bir öncelik haline gelmiştir. Bu kapsamda tahıllar, hem insan hem de hayvan beslenmesindeki yüksek payları ve endüstriyel kullanım alanlarının genişliği nedeniyle temel tarımsal ürün gruplarından birini oluşturmaktadır. Tahıllar içinde özellikle buğday *(Triticum aestivum* L.), geniş ekim alanı, yüksek üretim miktarı ve dünya nüfusunun büyük bir bölümünün temel besin kaynağını karşılaması bakımından ayrı bir öneme sahiptir. Nitekim FAO verilerine göre buğday, yaklaşık 215 milyon hektarlık ekim alanı ve 628 milyon tonluk üretimi ile dünya tahıl üretimi içerisinde ilk sırada yer almakta; tek başına küresel gıda kaynaklarının yaklaşık %20'sini ve toplam tahıl üretiminin yaklaşık %30'unu sağlamaktadır (FAO, 2023; Mızrak, 2011).

Buğday, yüksek adaptasyon yeteneği sayesinde oldukça farklı iklim ve toprak koşullarında yetiştirilebilmekte, bu özelliği onu birçok ülke için stratejik bir ürün konumuna getirmektedir. Dünya nüfusunun yaklaşık %35'ini oluşturan 40'tan fazla ülkede temel gıda maddesi olması, buğdayın küresel gıda güvenliği açısından kritik rolünü daha da pekiştirmektedir (Toklu ve ark. 2008).

Türkiye, buğdayın gen merkezi olması, geniş ekolojik çeşitliliğe sahip bulunması ve morfolojik-genetik varyasyonu yüksek yerel popülasyonları barındırması nedeniyle bu türün ıslahı ve üretim potansiyeli bakımından önemli bir avantaja sahiptir. Ancak sahip olunan bu potansiyele karşın, üretimde hâlen geleneksel uygulamaların yaygınlığı ve modern tarımsal teknolojilerin sınırlı düzeyde kullanılması, birim alan verimlerinin istenen seviyelere ulaşmasını güçleştirmektedir. Bu nedenle ekolojik koşullara uygun, yüksek verimli ve kaliteli çeşitlerin seçimi, uygun tohumluk kullanımı, doğru ekim zamanı, toprak hazırlığı, gübreleme, bakım ve hasat işlemlerinin optimize edilmesi büyük önem taşımaktadır (Bayramoğlu ve Gündoğmuş, 2010; Güngör ve Dumlupınar, 2019).

Bu çalışmada, tarafımızca yürütülen ıslah programı kapsamında geliştirilen 40 adet ekmeklik buğday hattının Sivas ili ekolojik koşullarındaki adaptasyon yetenekleri ve agronomik performansları değerlendirilmiştir. Araştırmanın temel amacı, bölge koşullarına en iyi uyum sağlayan, yüksek verimli ve kaliteli hatların belirlenerek ıslah sürecine bilimsel bir katkı sunulmasıdır. Elde edilecek üstün özelliklere sahip hatların yeni çeşit adayı olarak değerlendirilmesiyle, yörede buğday üretim verimliliğinin artırılması, çiftçi gelir düzeyinin yükseltilmesi ve dolaylı olarak ulusal ekonomiye katkı sağlanması hedeflenmiştir.

2. Materyal ve Metod

Araştırma, ekmeklik buğday hatlarının bölgesel adaptasyon yeteneklerinin belirlenmesi amacıyla, Sivas ili merkez ilçesinde yer alan çiftçi tarlasında 2024-2025 yetiştirme sezonunda yürütülmüştür.

Denemede 40 adet ekmeklik buğday hattı materyal olarak kullanılmıştır. Tarla denemeleri, tesadüf blokları deneme desenine göre 4 tekrarlamalı olarak yürütülmüştür. Ekim sıklığı m^2'de 500 tohum olacak şekilde planlanmıştır. Yetiştirme süresi boyunca gerekli kültürel işlemler eksiksiz olarak yerine getirilmiş, dekara 6 kg fosfor (P_2O_5) ile 15 kg azot (N) olacak şekilde gübreleme yapılmıştır. Fosforun tamamı ekimle birlikte taban gübresi olarak, azotun 1/3'ü ekimle, 1/3'ü kardeşlenme döneminde ve kalan 1/3'ü de sapa kalkma dönemlerinde elle serpilerek verilmiştir. Yabancı otlarla mücadele herbisit kullanılarak gerçekleştirilmiştir. Araştırmada, bitki boyu (cm), başak uzunluğu (adet), başakta tane sayısı (adet), başakta tane ağırlığı (g), bin tane ağırlığı (g) ve tane verimi (kg/da) özellikleri incelenmiştir. İstatistiki analizler JMP 7.0 istatistik paket programı kullanılarak gerçekleştirilmiştir.

3. Araştırma Bulguları ve Tartışma

Ekmeklik buğday gonotiplerinde saptanan agro-morfolojik karakterlere ilişkin ortalama, varyasyon katsayısı ve değişim sınırları değerleri Tablo1'de, incelenen bitkisel karakterlere

ilişkin ilk 6 ana bileşen için saptanan eigen ve varyans değerleri ile özelliklerin ana bileşendeki dağılımı Tablo 2'de verilmiştir. Tablo 1'in incelenmesinden; ele alınan bitkisel karakterler yönünden buğday gonotiplerinin önemli varyasyon gösterdiği; başakta tane sayısı, başakta tane ağırlığı ve bin tane ağırlığı gibi verim üzerinde doğrudan etkili bitkisel karakterler yönünden saptanan varyasyon katsayılarının oldukça yüksek olduğu görülmektedir.

Tablo 1. Buğday gen kaynaklarının tarımsal özellikleri için ortalama, standart sapma, en düşük ve en yüksek değerleri.

Özellik	Ortalama	Standart Sapma	En düşük	En yüksek
Bitki Boyu	87,35	17,36	53,20	125,70
Başak Uzunluğu (cm)	9,16	1,36	6,20	11,700
Başakta Tane Sayısı (adet)	32,45	4,21	24,90	41,10
Başakta Tane Ağırlığı (g)	1,69	0,37	1,19	2,74
Bin Tane Ağırlığı (g)	32,06	3,39	26,86	42,62
Tane Verimi (kg/da)	226,28	77,18	70,84	456,53

Tablo 2'nin incelenmesinden, incelenen altı ana bileşenin toplam varyasyonun %100'ünü açıkladığı, ilk dört ana bileşenin ise toplam varyasyonun %82.44'ünü temsil ettiği görülmektedir. Birinci ana bileşen (PRIN1), toplam varyasyonun %31.41'ini açıklamakta olup özellikle başakta tane ağırlığı, bin tane ağırlığı ve tane verimi ile pozitif; bitki boyu ile ise negatif yük değerleri sergilemektedir. Bu durum, yüksek tane verimi ve tane iriliği gösteren genotiplerin daha kısa bitki boyuna sahip olabildiğini ve verim unsurlarının bu bileşen üzerinde belirleyici olduğunu ortaya koymaktadır.

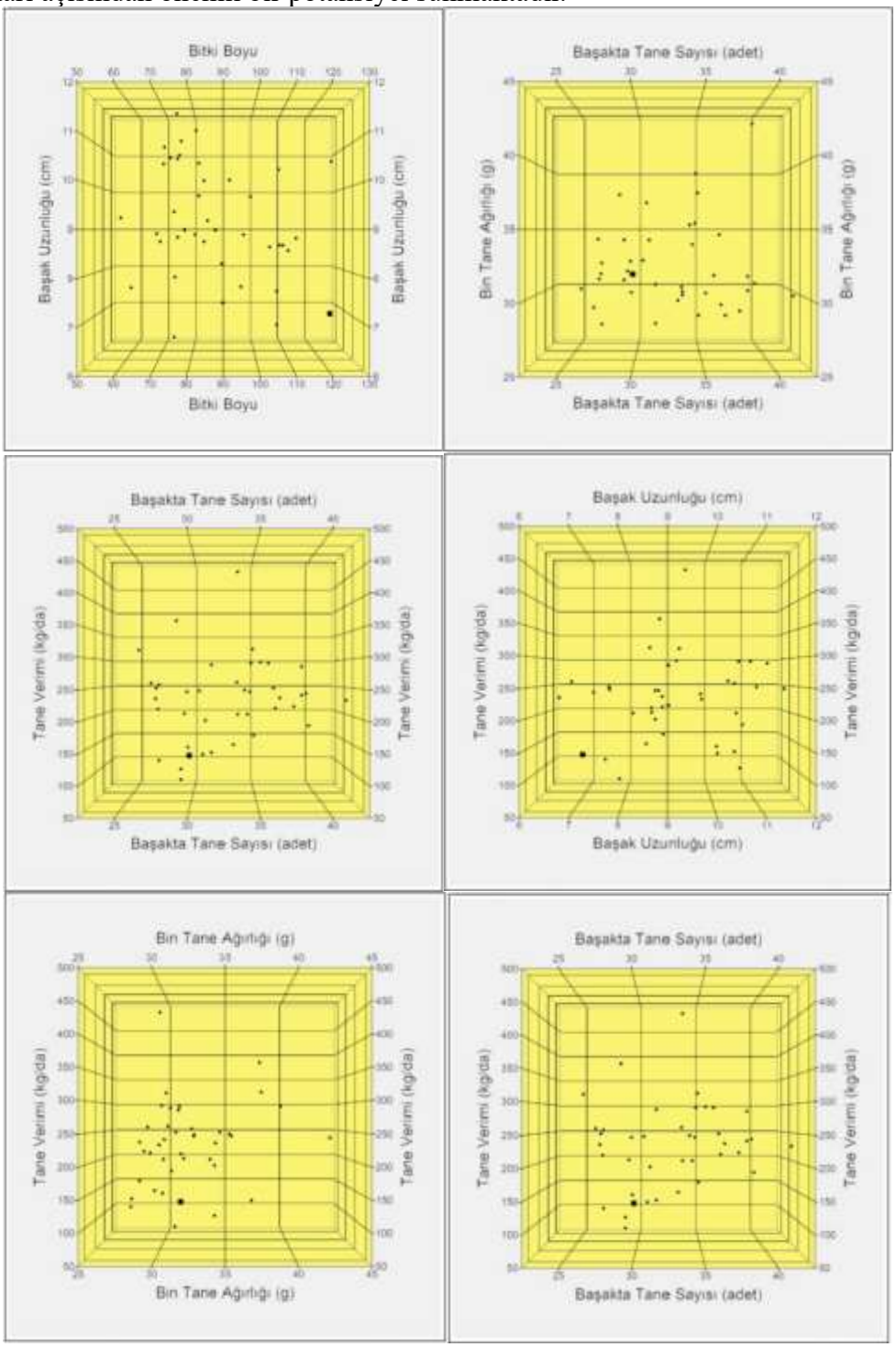
Tablo 2. İncelenen bitkisel karakterlere ilişkin ilk 6 ana bileşen için saptanan Eigen ve varyans değerleri ile özelliklerin ana bileşendeki dağılımı.

	PRIN 1	PRIN 2	PRIN 3	PRIN 4	PRIN 5	PRIN 6
Eigen değeri	1,8849	1,2126	1,0586	0,7902	0,6331	0,4207
Yüzde	31,414	20,209	17,644	13,169	10,551	7,012
Yığmalı yüzde	31,414	51,624	69,268	82,437	92,988	100,00
Bitki Boyu	-0,39592	0,04646	0,71694	0,19701	0,16569	0,51070
Başak Uzunluğu (cm)	0,31570	0,66460	-0,18320	-0,32240	0,33479	0,45723
Başakta Tane Sayısı (adet)	0,32295	0,52618	0,52418	0,08496	-0,37207	-0,44544
Başakta Tane Ağırlığı (g)	0,49020	-0,38948	0,16360	-0,29428	-0,52386	0,46928
Bin Tane Ağırlığı (g)	0,44515	-0,35622	0,35827	-0,19185	0,66245	-0,26636
Tane Verimi (kg/da)	0,44814	-0,02645	-0,15012	0,85242	0,09365	0,20135

İkinci ana bileşen (PRIN2), toplam varyasyonun %20.21'ini açıklamakta olup başak uzunluğu ve başakta tane sayısı ile güçlü pozitif; başakta tane ağırlığı ve bin tane ağırlığı ile ise negatif ilişkili bulunmuştur. Bu bulgu, uzun başaklı ve yüksek tane sayısına sahip genotiplerin, tane iriliği bakımından nispeten daha düşük değerlere sahip olabildiğini ve başak morfolojisinin bu bileşende ön plana çıktığını göstermektedir. Üçüncü ana bileşen (PRIN3), toplam varyasyonun %17.64'ünü açıklamakta olup bitki boyu ve başakta tane sayısı ile pozitif; tane verimi ile zayıf negatif ilişki sergilemektedir. Bu durum, uzun bitki boyuna ve yüksek tane sayısına sahip genotiplerin, her zaman yüksek tane verimi ile örtüşmeyebileceğini ortaya koymaktadır. Dördüncü ana bileşen (PRIN4) ise varyasyonun %13.17'sini açıklamakta olup özellikle tane verimi ile güçlü pozitif ilişki göstermektedir. Bu bileşende bitki boyu ve başakta tane sayısının etkisi sınırlı kalırken, doğrudan tane veriminin genotiplerin ayrışmasında belirleyici olduğu anlaşılmaktadır.

Literatürde de benzer şekilde, buğdayda tane veriminin çok sayıda morfolojik ve fizyolojik özelliğin birlikte etkisiyle şekillendiği, başak ve tane özellikleri arasındaki ilişkilerin genotip

ve çevre koşullarına bağlı olarak değişkenlik gösterebildiği bildirilmektedir (Atlı, 1999; Bayramoğlu ve Gündoğmuş, 2010). Sonuç olarak, ana bileşen analizi ile ekmeklik buğday genotipleri arasında verim ve verim unsurları bakımından geniş bir varyasyon bulunduğu ortaya konulmuştur. Bu genetik çeşitlilik, Sivas ve benzeri ekolojik koşullara uygun, yüksek verimli ve stabil performans gösteren yeni buğday çeşitlerinin geliştirilmesinde ıslah programları açısından önemli bir potansiyel sunmaktadır.



Şekil 1. Ekmeklik buğday (*Triticum aestivum* L.) genotiplerinin morfolojik ve kalite özelliklerine göre ana bileşen analizi (PCA-biplot) dağılım grafiği.

Şekil 1'de verilen PCA-biplot grafiği, incelenen ekmeklik buğday (Triticum aestivum L.) genotiplerinin morfolojik ve verim unsurlarına göre dağılımını ortaya koymaktadır. Genotiplerin ana bileşenler üzerindeki konumları, özellikler arasındaki ilişkileri ve genotipler arası varyasyonu görsel olarak yansıtmaktadır. Birinci ve ikinci ana bileşenler birlikte toplam varyasyonun %51.62'sini açıklamakta olup, genotiplerin temel agronomik özellikler bakımından ayrışmasında belirleyici rol oynamaktadır.

Birinci ana bileşen (PRIN1), toplam varyasyonun %31.41'ini açıklamakta olup başakta tane ağırlığı, bin tane ağırlığı ve tane verimi ile pozitif; bitki boyu ile negatif yük değerleri sergilemektedir. Buna göre biplot grafiğinin pozitif ekseninde yer alan genotipler yüksek tane verimi ve tane iriliği ile karakterize edilirken, negatif eksende konumlanan genotiplerin daha uzun bitki boyuna sahip olduğu görülmektedir. Bu durum, verim unsurları ile bitki boyu arasında ters yönlü bir ilişkinin varlığına işaret etmektedir.

İkinci ana bileşen (PRIN2) ise toplam varyasyonun %20.21'ini açıklamakta olup başak uzunluğu ve başakta tane sayısı ile güçlü pozitif; başakta tane ağırlığı ve bin tane ağırlığı ile negatif ilişki göstermektedir. Bu eksen boyunca üst bölgede yer alan genotiplerin uzun başaklı ve yüksek tane sayısına sahip olduğu, alt bölgede yer alan genotiplerin ise daha iri taneli özellikler sergilediği anlaşılmaktadır. Bu durum, başak morfolojisi ile tane iriliği arasında belirli bir denge ilişkisi bulunduğunu ortaya koymaktadır (Kendal ve Doğan, 2013).

Grafikte genotiplerin farklı eksenlerde kümelenmesi, incelenen özellikler bakımından genetik varyasyonun geniş olduğunu göstermektedir. Birbirinden uzak bölgelerde konumlanan genotipler, özellikle tane verimi, başak özellikleri ve tane iriliği yönünden belirgin farklılıklar sergilemekte olup, bu durum ıslah çalışmalarında ebeveyn seçiminde PCA-biplot analizinin etkin bir araç olduğunu ortaya koymaktadır (Bilgin ve ark., 2008).

Sonuç olarak, Şekil 1'de sunulan PCA-biplot grafiği, ekmeklik buğday genotiplerinin verim ve verim unsurlarına göre farklı gruplar oluşturduğunu ve bu grupların bölgeye uyumlu, yüksek verimli yeni çeşitlerin geliştirilmesinde önemli bir rehber niteliği taşıdığını göstermektedir. Özellikle ana bileşenler üzerinde birbirinden uzak konumlanan genotiplerin melezlenmesi, heterozis etkisinden yararlanılarak üstün kombinasyonların elde edilmesine katkı sağlayabilecektir (Genç ve Yağbasanlar, 2002).

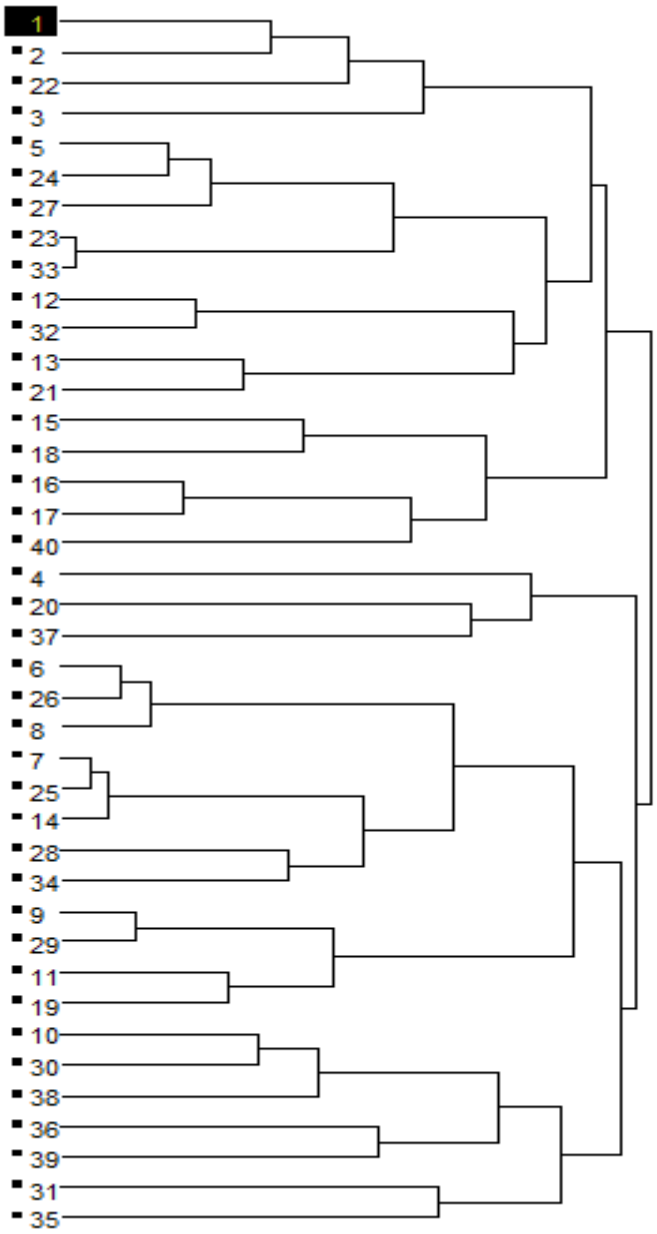
Şekil 2'de verilen UPGMA dendrogramı, incelenen ekmeklik buğday (Triticum aestivum L.) genotiplerinin morfolojik ve verim unsurlarına dayalı benzerlik–farklılık ilişkilerini ortaya koymaktadır. Dendrogramda genotiplerin farklı kümeler altında gruplandığı ve bu kümelenmenin bitki boyu, başak özellikleri, bin tane ağırlığı ve tane verimi gibi temel agronomik karakterler tarafından şekillendiği görülmektedir.

Genotiplerin ana kümeler ve alt gruplar halinde ayrışması, incelenen özellikler bakımından geniş bir genetik varyasyonun varlığına işaret etmektedir. Bazı genotiplerin dendrogramda birbirine yakın konumlanması, bu genotiplerin morfolojik ve verim unsurları yönünden benzer performans sergilediğini göstermektedir. Buna karşılık, bazı genotiplerin dendrogramda daha uzak dallarda yer alması, özellikle tane verimi, bin tane ağırlığı ve başak karakterleri bakımından belirgin farklılıklara sahip olduklarını ortaya koymaktadır (Özberk, ve ark., 2002).

Dendrogramda bağımsız veya yarı bağımsız konumlanan genotipler, morfolojik ve verim özellikleri yönünden diğer gruplardan ayrışmakta olup, bu genotiplerin genetik çeşitlilik açısından önemli bir potansiyel taşıdığı anlaşılmaktadır. Bu durum, söz konusu genotiplerin ıslah programlarında farklı ebeveyn kombinasyonları oluşturulmasında değerli materyaller olabileceğini göstermektedir (Özen ve Akman, 2014).

Sonuç olarak, UPGMA kümeleme analizi, ekmeklik buğday genotipleri arasında morfolojik ve verim unsurları bakımından anlamlı bir ayrışma bulunduğunu ortaya koymuştur. Bu kümelenme yapısı, özellikle ana kümeler arasında yer alan genotiplerin melezlenmesiyle,

yüksek verimli ve bölge koşullarına uyumlu yeni çeşitlerin geliştirilmesine yönelik ıslah çalışmalarında etkin bir rehber niteliği taşımaktadır (Khan ve ark., 2010).



Şekil 2. Ekmeklik buğday (*Triticum aestivum* L.) genotiplerinin morfolojik ve kalite özelliklerine göre hiyerarşik kümeleme dendrogramı (UPGMA).

4. Sonuç

Ana bileşen analizi (PCA) sonuçları, incelenen ekmeklik buğday (*Triticum aestivum L.*) genotipleri arasında morfolojik ve verim unsurları bakımından geniş bir varyasyon bulunduğunu açıkça ortaya koymuştur. Altı ana bileşenin toplam varyasyonun %100'ünü açıklaması, çalışmada değerlendirilen bitkisel karakterlerin genotipler arasındaki farklılıkları ayırt etmede yeterli ve etkili olduğunu göstermektedir. Özellikle ilk dört ana bileşenin toplam varyasyonun %82.44'ünü açıklaması, buğdayda verim ve verim unsurlarının genetik çeşitliliğin büyük bir bölümünü temsil ettiğini ortaya koymaktadır (Wiegand ve ark., 1981).

Birinci ana bileşen (PRIN1), toplam varyasyonun %31.41'ini açıklamakta olup başakta tane ağırlığı, bin tane ağırlığı ve tane verimi ile pozitif; bitki boyu ile negatif ilişki sergilemektedir.

Bu durum, yüksek tane verimi ve tane iriliğine sahip genotiplerin daha kısa bitki boyuna sahip olabildiğini ve verim unsurlarının bu bileşen üzerinde belirleyici rol oynadığını göstermektedir.

İkinci ana bileşen (PRIN2), varyasyonun %20.21'ini açıklamakta olup başak uzunluğu ve başakta tane sayısı ile güçlü pozitif; başakta tane ağırlığı ve bin tane ağırlığı ile negatif ilişkili bulunmuştur. Bu bulgu, uzun başaklı ve yüksek tane sayısına sahip genotiplerde tane iriliğinin nispeten azalabildiğini ve başak morfolojisinin bu bileşende ön plana çıktığını ortaya koymaktadır (Zafarnaderi ve ark., 2013).

Üçüncü ana bileşen (PRIN3), toplam varyasyonun %17.64'ünü açıklamakta olup bitki boyu ve başakta tane sayısı ile pozitif, tane verimi ile zayıf negatif ilişki göstermektedir. Bu durum, uzun bitki boyu ve yüksek tane sayısının her zaman yüksek tane verimi ile örtüşmeyebileceğini, verimin çok sayıda bileşenin birlikte etkisiyle şekillendiğini göstermektedir.

Dördüncü ana bileşen (PRIN4) ise varyasyonun %13.17'sini açıklamakta olup özellikle tane verimi ile güçlü pozitif ilişki sergilemektedir. Bu bileşen, doğrudan tane veriminin genotiplerin ayrışmasında belirleyici bir faktör olduğunu ortaya koymakta; bitki boyu ve başak özelliklerinin bu eksende ikincil düzeyde etkili olduğunu göstermektedir (Kara ve ark., 2016). Bu bulgular, ekmeklik buğday ıslah programları açısından büyük önem taşımaktadır. Çünkü ebeveyn seçiminde genotiplerin yalnızca tek bir özellik yönünden değil, verim ve verim unsurlarının birlikte değerlendirilmesi gerekmektedir. PCA ile ortaya konulan bu varyasyon yapısı, farklı özellik kombinasyonlarına sahip genotiplerin belirlenmesine ve birbirini tamamlayıcı ebeveynlerin seçilmesine olanak sağlamaktadır. Özellikle ana bileşenler üzerinde birbirinden uzak konumlanan genotiplerin melezlenmesi, heterozis etkisinden yararlanılarak hem yüksek verimli hem de stabil performans gösteren yeni çeşitlerin geliştirilmesine katkı sağlayabilecektir (Özgen, 1989).

Sonuç olarak, PCA sonuçları, incelenen buğday genotipleri arasında önemli morfolojik ve agronomik farklılıkların bulunduğunu ve bu farklılıkların ıslah çalışmalarında etkin şekilde değerlendirilebileceğini ortaya koymuştur. Elde edilen bulgular, Sivas ve benzeri ekolojik koşullara uygun, yüksek verimli ve adaptasyon yeteneği güçlü yeni ekmeklik buğday çeşitlerinin geliştirilmesi açısından önemli bir bilimsel temel sunmaktadır.

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YANMA ODASINDA DOĞALGAZ-HİDROJEN KARIŞIMININ YANMA VERİMLİLİĞİNİN HESAPLAMALI AKIŞKANLAR DİNAMİĞİ İLE İNCELENMESİ

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ÖZET

Hidrojen, yüksek yanma verimliliği, geniş tutuşma aralığı ve düşük karbon emisyonu özellikleri nedeniyle fosil yakıtlarla birlikte kullanılarak alternatif bir enerji kaynağı olarak öne çıkmaktadır. Enerji üretim sistemlerinde karbon ayak izinin azaltılması, sera gazı salınımlarının düşürülmesi ve sürdürülebilir yakıt dönüşümünün sağlanması açısından hidrojenin doğalgazla birlikte kullanımı son yıllarda büyük önem kazanmıştır. Bu çalışmada, doğalgaz-hidrojen karışımlarının yanma odasındaki termal ve akışkan dinamiği davranışı Hesaplamalı Akışkanlar Dinamiği (CFD) yöntemleriyle analiz edilmiştir. Simülasyonlarda hidrojenin farklı hacim oranları (%0, %20, %40, %60 ve %80) dikkate alınarak sıcaklık dağılımı, türbülans yapısı, yanma verimliliği ve NOx emisyonlarının değişimi incelenmiştir. Yanma süreci, detaylı kimyasal kinetik mekanizmalarla modellenmiş ve türbülans–kimyasal etkileşimler ANSYS Fluent 18.1 yazılımı kullanılarak analiz edilmiştir. Çalışma kapsamında altı girişli silindirik bir yanma odası geometrisi seçilmiş, ağ bağımsızlık analizi gerçekleştirilmiş ve Reynolds Gerilme Modeli (RSM) kullanılarak dönel akış etkileri değerlendirilmiştir. Elde edilen sonuçlar, hidrojen oranının artışıyla birlikte alev sıcaklığında, reaksiyon hızlarında ve yanma verimliliğinde belirgin artışlar meydana geldiğini göstermektedir. Ancak sıcaklık artışına paralel olarak termal NOx oluşum mekanizmasının güçlendiği ve emisyon değerlerinde yükselme eğilimi gözlenmiştir. Bu bulgular, doğalgaz-hidrojen karışımlı sistemlerin optimum karışım oranlarının belirlenmesi, alev stabilitesinin korunması ve NOx oluşumunun kontrol edilmesi açısından önemli veriler sunmaktadır. Sonuç olarak, çalışma, hidrojenin enerji dönüşüm sistemlerine entegrasyonunda sürdürülebilir ve düşük emisyonlu yanma stratejilerinin geliştirilmesine katkı sağlamaktadır.

Anahtar Kelimeler: doğalgaz-hidrojen yanması, Hesaplamalı Akışkanlar Dinamiği (CFD), NOx emisyonu

INVESTIGATION OF THE COMBUSTION EFFICIENCY OF A NATURAL GAS-HYDROGEN MIXTURE IN A COMBUSTION CHAMBER USING COMPUTATIONAL FLUID DYNAMICS

ABSTRACT

Hydrogen has emerged as an alternative energy source due to its high combustion efficiency, wide flammability range, and low carbon emission characteristics. In recent years, the co-combustion of hydrogen with natural gas has gained significant attention for reducing the carbon footprint of energy production systems, decreasing greenhouse gas emissions, and enabling a sustainable fuel transition. In this study, the thermal and fluid dynamic behavior of natural gas–hydrogen mixtures inside a combustion chamber was analyzed using Computational Fluid Dynamics (CFD) methods. Simulations were performed by considering different hydrogen volume fractions (0%, 20%, 40%, 60%, and 80%) to investigate variations in temperature distribution, turbulence structure, combustion efficiency, and NOx emissions. The combustion process was modeled using detailed chemical kinetic mechanisms, and turbulence–chemistry interactions were analyzed with the ANSYS Fluent 18.1 software. A six-inlet cylindrical combustion chamber geometry was selected, a mesh independence study was carried out, and the effects of swirling flow were evaluated using the Reynolds Stress Model (RSM). The obtained results reveal that increasing the hydrogen fraction significantly enhances flame temperature, reaction rate, and combustion efficiency. However, a parallel increase in thermal NOx formation was observed due to the higher temperature levels. These findings provide valuable insights into determining the optimal mixing ratios, maintaining flame stability, and controlling NOx formation in natural gas–hydrogen combustion systems. Consequently, this study contributes to the development of sustainable and low-emission combustion strategies for the integration of hydrogen into modern energy conversion systems.

Keywords: natural gas-hydrogen combustion, Computational Fluid Dynamics (CFD), NOx emissions

1. GİRİŞ

Günümüzde enerji ihtiyacının sürekli olarak artması, çevre açısından fosil yakıtlara olan bağımlılığın azaltılmasını ortaya koymakta ve sürdürülebilir, düşük emisyon değerlerine sahip enerji kaynaklarının araştırılmasını zorunlu hale getirmiştir. Endüstriyel proseslerde, enerji üretim tesislerinde ve jeneratörler vb. Enerji üretiminde yaygın olarak kullanılan doğalgaz, düşük karbon salınımı ve yüksek enerji yoğunluğu nedeniyle tercih edilen bir yakıt türü olsa da tamamen karbonsuz bir enerji kaynağı değildir. Küresel ısınma ve iklim değişikliği ile mücadele kapsamında, karbon içermeyen veya düşük karbonlu alternatif yakıtlar enerji sektöründe büyük bir önem kazanmıştır. Bu amaçla hidrojen, yüksek enerji taşıma kapasitesi, geniş tutuşma aralığı ve sıfır karbon emisyonu ile doğalgazın kısmen veya tamamen yerine geçebilecek potansiyel bir yakıt olarak ön plana çıkmaktadır.

Hidrojenin yanma özellikleri, doğalgazdan farklılıklar göstermektedir. Hidrojenin tutuşma hızı, ısıl iletkenliği ve alev sıcaklığı, doğalgaza kıyasla önemli ölçüde yüksektir. Ayrıca, hidrojenin karışım oranı arttıkça, yanma hızı ve sıcaklık profili değişmekte, bu durumda yanma odasındaki akış özelliklerini etkilemektedir. Ancak, hidrojenin düşük yoğunluğu, yüksek difüzyon katsayısı ve yüksek alev sıcaklığı, yanma sürecinde yanma kararsızlıkları ve NOx emisyonlarının artışı gibi olumsuz etkilere yol açabilmektedir. Bu nedenle, hidrojenin doğalgaz birlikte kullanıldığı sistemlerde karışım oranlarının dikkatli bir şekilde belirlenmesi ve yanma performansı ile emisyon seviyelerinin optimize edilmesi gerekmektedir.

Doğalgaz-hidrojen karışımlı yanma sistemleri üzerine yapılan çalışmalar, farklı hidrojen yüzdelerinin yanma karakteristikleri ve emisyonlara etkisini incelemektedir. Hidrojen oranının artışı, alev sıcaklığını ve yanma hızını artırarak daha verimli bir yanma süreci sağlarken, aynı zamanda NOx emisyonlarının yükselmesine neden olabilir. Bu durumda, hava fazlalık katsayısı, türbülans seviyesi ve yanma odası geometrisi gibi parametreler, hidrojen içeriğine bağlı olarak yanma sürecinin stabilitesini ve verimliliğini belirleyen temel faktörler arasında yer almaktadır.

Yapılan çalışmada, silindirik bir yanma odasında hidrojen-doğalgaz karışımlarının yanma performansı ve emisyon karakteristikleri incelenmiştir. ANSYS Fluent yazılımı kullanılarak yapılan Hesaplamalı Akışkanlar Dinamiği (CFD) analizleri ile farklı hidrojen hacim oranları altında (hacmen %0, %20, %40, %60 ve %80 H_2) yanma sürecinin sıcaklık dağılımı, NOx emisyonları ve akış özellikleri değerlendirilmiştir. Hidrojen yüzdesinin artışına bağlı olarak yanma sıcaklıkları, NOx emisyon seviyeleri ve alev karakteristikleri arasındaki ilişki detaylı bir şekilde analiz edilmiştir.

2. LİTERATÜR ÖZETİ

Shabanian vd. 2010 yılında hidrojen-hava ön karışımının mikro yanma odasında farklı fiziksel ve sınır koşulları altındaki davranışlarını araştırmıştır. Çalışmada, farklı çap ve uzunluktaki mikro yanma odalarında alev sıcaklığı dağılımını analiz edilmiştir. Yanma odasının boyutu küçüldükçe, yüzey alanı/hacim oranı arttığı için ısı kaybının arttığı ve alev sıcaklığının düştüğü tespit edilmiştir. Hidrojen beslemesinin bölünmesi, yanma odası içindeki sıcaklık dağılımını daha homojen hale getirerek maksimum sıcaklığı önemli ölçüde azalttığı tespit edilmiştir (Shabanian vd., 2010).

Yapılan derleme çalışmasında Shchepakina vd., hidrojen yanmasının fiziksel ve kimyasal özelliklerini ve bunların gaz türbini yanma odalarının performansı üzerindeki etkilerini araştırmıştır. Hidrojenin daha yüksek laminer alev hızı, düşük ateşleme gecikmesi ve geniş tutuşma aralıkları sunduğunu bulmuşlardır. Hidrojen eklenmesi, alev kompaktlaşmasına ve boyutunun küçülmesine neden olmaktadır. Ayrıca hidrojenin adyabatik yanma sıcaklığının

metandan %5-15 daha yüksek olduğu tespit edilmiştir. Bu da yanma odası ve türbin bileşenlerinin termal yüklerini artırmaktadır (Shchepakina vd., 2023).

ABD Enerji Bakanlığı tarafından desteklenen bu çalışmada, hidrojen ve doğal gaz türbinlerinin performansını ve NO_x kontrol yöntemleri incelenmiştir. Hidrojenin, daha yüksek alev hızı ve düşük ateşleme enerjisi nedeniyle termal NO_x oluşumunu artırdığı ve bu durumun yanma kararsızlıklarına neden olduğu belirlenmiştir. Hidrojenle çalışan gaz türbinlerinde düşük NOx emisyonları sağlamak için selektif katalitik indirgeme (SCR) gibi modern yöntemlerin uygulanmasının gerekli olduğu vurgulanmıştır (NETL, 2022).

Kumar vd. hidrojen ile zenginleştirilmiş sıkıştırılmış doğal gazın (CNG) direkt enjeksiyonlu ateşleme motorlarındaki jet karakteristiklerini analiz etmiştir. Hidrojenin, CNG'ye kıyasla daha kısa jet penetrasyon uzunluğu (%2) ve daha yüksek jet alanı (%1–3) gösterdiği tespit edilmiştir. Hidrojenin daha yüksek difüzyon oranı ve hızlı karışımı, CNG'ye kıyasla yakıt-hava karışımını geliştirmektedir. Ancak %10, %20 ve %40 oranında hidrojenle zenginleştirilmiş CNG'nin jet karakteristiklerinde önemli bir değişiklik gözlemlenmemiştir (Kumar vd., 2024).

Xu vd. çalışmasında, farklı jet yoğunluklarının (Pjet), hidrojen katkı oranlarının (XH2) ve eşdeğerlik oranlarının (φ) çok bileşenli doğal gaz/hidrojen karışımının patlama karakteristikleri üzerindeki etkileri incelenmiştir. Pjet arttıkça, maksimum basınç (Pmax) ve basınç artış hızı ((dp/dt)max) ilk etapta artmış ve daha sonra azalmıştır. En iyi performans Pjet = 0.4 MPa'da elde edilmiştir. XH2 arttıkça Pmax artarken, patlama süresi azalmıştır. Bu çalışma, doğal gaz/hidrojen karışımlarının patlama tehlikeleri açısından önemli bir referans sağlamaktadır (Xu vd., 2024).

Lucas vd. yaptıkları çalışmada, FLACS-CFD simülasyonları kullanarak hidrojen ve metan-hidrojen karışımlarının farklı oksijen konsantrasyonları ve eşdeğerlik oranları altındaki patlama dinamiklerini analiz etmiştir. Hidrojen içeren karışımlarda, patlama basıncının ve alev hızının oksijen konsantrasyonuna duyarlı olduğu görülmüştür. Özellikle zengin hidrojen karışımlarında patlama basıncının artış gösterdiği ve alev yayılım hızlarının arttığı tespit edilmiştir. FLACS-CFD 22.1 IH sürümünün, zengin hidrojen karışımları için basınç tahminlerinde daha doğru sonuçlar verdiği gösterilmiştir (Lucas vd., 2023).

Algayyim vd. yaptıkları kapsamlı inceleme çalışmasında, doğal gaz (NG) ve hidrojenin içten yanmalı motorlarda (IC) performans, yanma ve emisyonlar üzerindeki etkilerini değerlendirmiştir. Doğalgazın buji ateşlemeli (SI) motorlardaki verimliliği ve emisyon performansı incelenmiş, hidrojenin yüksek ateşleme sıcaklığı nedeniyle NOx emisyonlarında artışa yol açtığı tespit edilmiştir. Çalışmada, hidrojen ilavesinin motor verimliliğini artırırken, emisyonları azaltabileceğini, ancak motor tasarımı ve güvenlik önlemleri açısından bazı zorluklar yarattığını vurgulamıştır (Algayyim vd., 2024).

Ghazal vd. tarafından yapılan derleme çalışmasında, hidrojen ile zenginleştirilmiş gaz yakıtlarının yanma karakteristikleri üzerindeki etkilerini incelenmiştir. Hidrojenin daha yüksek ateşleme hızı ve yanma sıcaklığı nedeniyle NOx oluşumunun arttığı, ancak düşük hidrojen konsantrasyonlarının yanma verimliliğini ve stabilitesini iyileştirdiği gözlemlenmiştir. Çalışmada ayrıca, düşük ve orta dereceli hidrojen katkılarının yanma odası performansını artırırken, yüksek hidrojen oranlarının patlama ve güvenlik riskleri yarattığını göstermiştir (Ghazal vd., 2024).

3. MATERYAL METOT

Fosil yakıt kaynaklarının sınırlı olması ve yanma süreçlerinin çevresel etkileri, yenilenebilir ve temiz enerji kaynaklarına olan ilgiyi artırmıştır. Doğalgaz, diğer fosil yakıtlara kıyasla daha

düşük CO_2 emisyonlarına sahip olsa da net sıfır karbon hedeflerine ulaşmak için tamamen karbonsuz enerji kaynaklarına yönelmek gerekmektedir. Bu noktada hidrojen, yenilenebilir enerji kaynaklarından üretilebilmesi ve yanma sonrası yalnızca su buharı açığa çıkarması nedeniyle küresel ölçekte en önemli alternatiflerden biri olarak değerlendirilmektedir.

Hidrojenin doğalgaz ile kullanımı, mevcut altyapının korunmasını sağlarken, düşük karbonlu bir geçiş süreci oluşturma avantajı sunmaktadır. Ancak, hidrojenin düşük yoğunluğu ve yüksek reaktivitesi, yanma sürecinde özel optimizasyon gerektiren faktörlerdir. Bu nedenle, hidrojenin doğalgaz ile kullanıldığı sistemlerde yanma dinamiklerinin kapsamlı bir şekilde analiz yapılmıştır.

Hidrojen-doğalgaz karışımlarıyla çalışan yanma sistemlerinin performans analizinde, deneysel çalışmaların yüksek maliyetli ve zaman alıcı olması, Hesaplamalı Akışkanlar Dinamiği (CFD) analizlerini önemli bir alternatif haline getirmiştir. CFD analizleri, yanma sürecindeki sıcaklık, akış ve türbülans dağılımlarını detaylı bir şekilde inceleyerek sistem optimizasyonu konusunda önemli veriler sunmaktadır.

Hesaplamalı Akışkanlar Dinamiği (CFD) de kullanılan temel denklemler; kütle, momentum, enerji ve maddenin korunumu şeklindedir.

Kütlenin Korunumu

$$\frac{\delta p}{\delta t} + \nabla.(\rho u) = 0$$

Momentumun Korunumu

$$\rho\left(\frac{\delta u}{\delta t} + (u.\nabla)u\right) + \nabla p = \rho g + f + \nabla.\tau$$

Enerjinin Korunumu

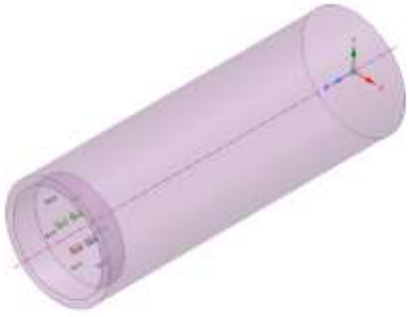
$$\frac{\delta(\rho h)}{\delta t} + \nabla.\rho h u - \frac{Dp}{Dt} = \dot{q}''' - \nabla.q_r + \nabla.q_r + \nabla.k\nabla T + \nabla\sum_l h_l(\rho D)_l \nabla Y_l$$

Maddenin Korunumu

$$\frac{\delta(\rho Y_l)}{\delta t} + \nabla.\rho Y_l u = (\rho D)_l \nabla Y_l + w_i'''$$

3.1. Yanma Odası Özellikleri

Altı girişli silindir yanma odasının konfigürasyonu Şekil 1.'de tasarımsal olarak gösterilmiştir. Yanma odasının her biri 20 mm çapında altı tane teğetsel girişi ve 700 mm çapında bir çıkışı bulunmaktadır.



Şekil 1. Yanma odası tasarımı

Boyutlar şu şekildedir:

Yanma odası çapı: De = 1850 mm

Giriş çapı: Di = 20 mm

Çıkış çapı: Do = 700 mm

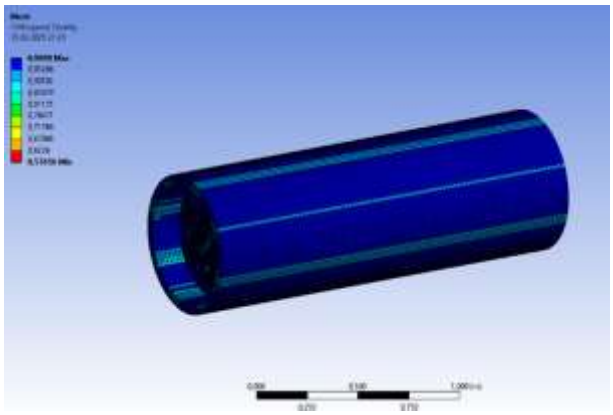
Yanma odası uzunluğu: Lc = 1850 mm

Farklı karışım oranlarında sayısal çalışmalar yapılmıştır. Sonuç olarak, silindir yanma odası doğalgaz-hidrojen karışımı ile başarıyla çalıştırılmıştır.

3.2. Yanma Odasının CFD Modellenmesi

Altı girişli silindir yanma odasının CFD modellemesinde, NO_x post-prosesi ile entegre edilerek yapılmıştır. Tüm sayısal analizler için oda sıcaklığı için 300 K varsayılmıştır.

Yanma reaksiyonlarının, yanma odasında güçlü dönme akışıyla meydana geldiği göz önüne alındığında, ağ yapısının incelenmesi sağlanmak için yapılandırılmıştır. Ağ bağımsızlığını sağlamak amacıyla, farklı eleman sayılarıyla dört farklı ağ yapısı kullanılmıştır. Ağ hassasiyet analizine göre, 450000 hücreden daha az eleman içeren ağ yapılarında 250000 eleman ve 300000 eleman modelleme sonuçları kabul edilebilir bulunmamıştır. Ancak, daha fazla ağ kullanıldığında 1000000 eleman sonuçlar arasında belirgin bir fark olmadığı gözlemlenmiştir. Bu nedenle, 439412 hücre hücreli ve 451721 düğümlü Hexahedral hücrelerine sahip ağ yapısı, sonraki modelleme için uygun ağ yapısı olarak seçilmiştir. Ağ kalitesine bakıldığında, en yüksek eğrilik değeri 0,81809, ortalama eğrilik değeri ise 0,22241'dir. Oluşturulan ağ yapısının en düşük ortogonal kalite değeri ise 0,119'dur.



Şekil 2. Yanma odasına uygulanan ağ yapısı

Silindir yanma odalarında meydana gelen dönme hareketli türbülanslı akışı modellemek için iki farklı türbülans modeli, k-ε ve RSM, kullanılmaktadır. Her iki türbülans modelinin sonuçları mevcut deneysel verilerle karşılaştırılmıştır. RSM, ANSYS FLUENT'in en kapsamlı türdeki türbülans modelidir. Temelde, RSM, hız ve uzunluk değerlerinin yönle değiştiği karmaşık akışlarda daha iyi sonuçlar verir.

RSM, yanma odasında yüksek dönme akışı üretildiği için en iyi sonuçları vermiştir. Bu akışta hız ve uzunluk ölçekleri yönle değişir. RSM türbülans modelinde, bireysel Reynolds gerilmeleri hesaplanırken, k-ε modelinde izotropik varsayımı yapılmaktadır.

4. SİMULASYON DEĞERLERİ

Yanma sürecinde akış dinamikleri, yanma odasındaki alev stabilitesi, sıcaklık dağılımı ve emisyon oluşumu üzerinde doğrudan etkili olan kritik bir faktördür. Hidrojenin doğalgaz ile

kullanımı hem yanma hızını hem de akış karakteristiklerini değiştirerek yanma sürecinin termodinamik ve kimyasal yapısını farklılaştırır. Bu bölümde, hidrojenin yanma odasındaki akış hızlarına ve türbülansa etkisi detaylı olarak analiz edilmiştir.

4.1. Hidrojen Oranının Yanma Sıcaklığı Üzerine Etkisi

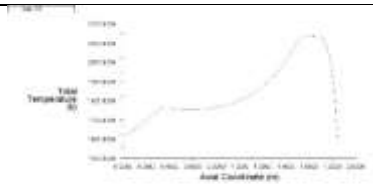
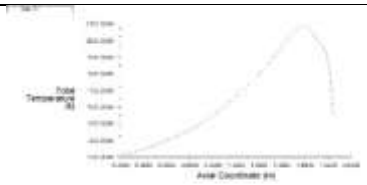
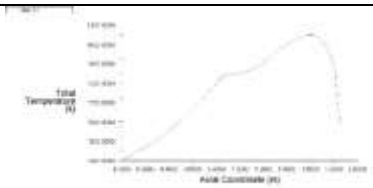
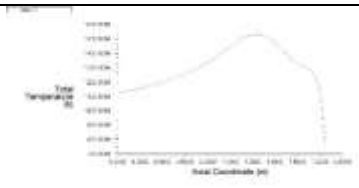
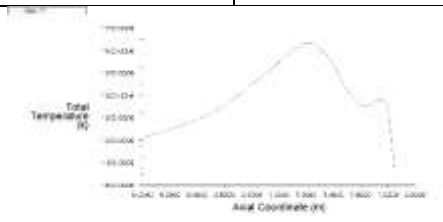
Hidrojenin doğalgaza eklenmesi, alev sıcaklığını artıran bir etkiye sahiptir. Bunun başlıca nedenleri şunlardır:

•Hidrojenin alt ısıl değeri (LHV), doğalgaza göre farklıdır. Metan (CH_4) için alt ısıl değer yaklaşık 50 MJ/kg iken, hidrojen için 120 MJ/kg seviyesindedir. Bu, aynı enerji girişinde hidrojenin daha yüksek bir sıcaklığa ulaşmasını sağlar.

•Hidrojenin tutuşma hızı metana kıyasla çok daha yüksektir. Hidrojenin laminer yanma hızı yaklaşık 2,91 m/s iken, metanın yanma hızı 0,39 m/s civarındadır. Bu, yanma sürecinin daha hızlı tamamlanmasına ve daha yüksek sıcaklıkların oluşmasına neden olur.

Hidrojenin difüzyon katsayısı yüksektir. Bu durum, oksijenle daha hızlı ve homojen bir şekilde karışmasını sağlar, böylece yanma verimliliğini artırır ve sıcaklık dağılımını etkiler. Yapılan deneysel ve sayısal çalışmalar, hidrojen oranının artmasıyla birlikte yanma sıcaklıklarının belirgin şekilde yükseldiğini göstermektedir. Örneğin, hidrojen oranı %0'dan %80'e çıkarıldığında, yanma sıcaklığının arttığı gözlemlenmektedir.

Yapılan çalışma ile de hidrojenin hacimsel yüzde miktarına bağlı olarak elde edilen sonuçların grafikleri Şekil 3.'te ve değerleri Tablo 1.'de verilmiştir.

<table>
<tr><td></td><td></td></tr>
<tr><td>Hacmen %20 Doğalgaz %80 Hidrojen</td><td>Hacmen %60 Doğalgaz %40 Hidrojen</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Hacmen %40 Doğalgaz %60 Hidrojen</td><td>Hacmen %80 Doğalgaz %20 Hidrojen</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">Hacmen %100 Doğalgaz %0 Hidrojen</td></tr>
</table>

Şekil 3. Hacim olarak doğalgaz ve hidrojen değerleri

Tablo 1. CH_4 / H_2 Hacimsel oranına göre maksimum yanma sıcaklığı değerleri (K)

CH_4 / H_2 Hacimsel Oranı	**Maksimum Yanma Sıcaklığı (K)**
1,0 CH_4 (Saf Doğalgaz)	1111,4772 K
0,8 CH_4 / 0,2 H_2	1006,452 K
0,6 CH_4 / 0,4 H_2	1118,3559 K
0,4 CH_4 / 0,6 H_2	1146,7545 K
0,2 CH_4 / 0,8 H_2	1313,8104 K

4.2. Hidrojen Oranının NOx Emisyonları Üzerine Etkisi

NOx emisyonları, yanma sürecinde ısı, oksijen varlığı ve azot gazının tepkimeye girmesiyle oluşur. Hidrojen oranının artışı, NOx emisyonlarının değişmesine neden olan birkaç temel mekanizmaya sahiptir:

• Termal NOx oluşumu: Yüksek sıcaklıklarda, havadaki azot (N_2) oksijenle birleşerek NOx oluşturur. Hidrojenin eklenmesiyle yanma sıcaklıkları arttığı için, termal NOx mekanizması daha etkili hale gelir.

• Yakıt NOx oluşumu: Hidrojen içeren karışımlarda yakıt içerisinde azot bulunmadığı için yakıt kaynaklı NOx oluşumu azalır. Bu, hidrojenin emisyon kontrolü açısından avantajlı olmasını sağlar.

• Prompt NOx oluşumu: Yanma bölgesindeki serbest radikallerin, azot gazı ile etkileşime girmesi sonucu oluşur. Hidrojenin yüksek reaktivitesi nedeniyle prompt NOx oluşumu hidrojen içeriğinin artışıyla bir miktar azalabilir.

Deneysel çalışmalar, hidrojen oranı arttıkça NOx emisyonlarının genellikle yükseldiğini göstermektedir. Örneğin, hidrojen hacim oranının %20'den %80'e çıkmasıyla NOx emisyonlarının 2 katına çıkabileceği tahmin edilmektedir. Ancak, Yakıt-hava oranının optimize edilmesi ve yanma sıcaklığının kontrol altında tutulması, NOx oluşumunu azaltmak için kritik bir faktördür (Shere & Subramanian, 2024).

Tablo 2. Hidrojen oranının NOx emisyon değerleri

CH_4 / H_2 Hacimsel Oranı	**NOx Emisyonu (ppm)**
1,0 CH_4 (Saf Doğalgaz)	78 ppm
0,8 CH_4 / 0,2 H_2	112 ppm
0,6 CH_4 / 0,4 H_2	156 ppm
0,4 CH_4 / 0,6 H_2	188 ppm
0,2 CH_4 / 0,8 H_2	215 ppm

• Hidrojen yüzdesi %20’ye kadar çıktığında NOx artışı daha yavaş gerçekleşmiştir.

• %40 H_2 ve üzerindeki karışımlarda, sıcaklık artışı ile NOx seviyesi belirgin şekilde yükselmiştir.

• %80 H_2 seviyesinde NOx değeri maksimum seviyeye ulaşmış ve 215 ppm olarak ölçülmüştür.

4.2.1. NOx Emisyonlarını Azaltma Stratejileri

Hidrojen yüzdesi arttıkça NOx emisyonları yükseldiği için, yanma odasında NOx kontrolü sağlamak adına bazı stratejiler uygulanabilir:

•Yakıt zengin karışımlarda yanma daha düşük NOx seviyeleri sağlayabilir.

•Yanma odasına fazla hava vererek alev sıcaklığını kontrol etmek termal NOx oluşumunu azaltabilir.

•Yanma hızını düşüren türbülans kontrollü sistemler kullanmak NOx oluşum mekanizmasını yavaşlatabilir.

Bu analizler, hidrojenin yanma verimliliğini artırırken NOx emisyonlarını da önemli ölçüde etkilediğini göstermektedir. Yanma sıcaklığının kontrol altında tutulması ve oksidasyon süreçlerinin optimize edilmesi, hidrojen-doğalgaz karışımlarının sürdürülebilir enerji üretiminde daha verimli kullanılmasını sağlayacaktır.

4.3. Hidrojen Oranının Akış Karakteristiği Üzerindeki Etkisi

Yanma odasındaki akış dağılımı, yakıtın türbülanslı karışımı, türbülans enerjisi dağılımı ve alevin stabilitesi açısından değerlendirilmelidir. Hidrojenin doğalgaz ile kullanımı, aşağıdaki faktörler üzerinde önemli etkilere sahiptir:

1.Artan Akış Hızı ve Difüzyon

Hidrojenin düşük moleküler ağırlığı (2,016 g/mol), doğalgaza kıyasla çok daha hafif bir akış profili oluşturmasını sağlar.

Hidrojenin gaz fazındaki difüzyon katsayısı metana kıyasla yaklaşık 7 kat daha yüksektir, bu nedenle yanma bölgesinde daha hızlı yayılır.

2.Türbülans ve Karışım Kalitesi

Hidrojenin yanma odasındaki türbülansı artırdığı gözlemlenmiştir.

%40 H_2 ve üzerindeki karışımlarda, yanma odasında yüksek girdap bölgeleri oluşmuş ve türbülans kinetik enerjisi artmıştır.

Bu artış, yanma sürecinin verimliliğini artırırken, alev stabilitesini etkileyebilir.

3.Hidrojenin Hızlı Yanması ve Alev Stabilitesi

Hidrojen, metana kıyasla 7 kat daha hızlı yanar, bu da yanma bölgesinde alev hızını artırır.

Yüksek hidrojen oranlarında (> %60 H_2), yanma odasında alev geri tepmesi (flashback) riski oluşabilir.

Alev stabilitesi açısından, %20-40 H_2 içeren karışımların daha dengeli bir yanma sağladığı gözlemlenmiştir.

ANSYS Fluent kullanılarak farklı doğalgaz-hidrojen oranları altında akış hızları ve türbülans dağılımı analiz edilmiştir. Elde edilen maksimum hız değerleri Tablo 3'te verilmiştir:

Tablo 3. Hidrojen oranının maksimum akış hızları (m/s)

CH_4 / H_2 Hacimsel Oranı	**Maksimum Akış Hızı (m/s)**
1.0 CH_4 (Saf Doğalgaz)	23,4 m/s
0.8 CH_4 / 0.2 H_2	28,2 m/s
0.6 CH_4 / 0.4 H_2	31,7 m/s
0.4 CH_4 / 0.6 H_2	35,1 m/s
0.2 CH_4 / 0.8 H_2	39,6 m/s

Sonuçlar, hidrojen oranı arttıkça maksimum akış hızının belirgin şekilde yükseldiğini göstermektedir. %100 metan yakıtında 23,4 m/s olan hız, %80 hidrojen içeren karışımda 39,6 m/s'ye kadar çıkmıştır. Bu artışın temel nedenleri:

Hidrojenin düşük yoğunluğu nedeniyle daha hızlı bir akış profili oluşturması,

Hidrojenin yüksek difüzyon katsayısı nedeniyle türbülansın artması,

Hidrojenin yüksek tutuşma hızı nedeniyle yanma bölgesinde daha hızlı reaksiyon gerçekleşmesi olarak açıklanabilir.

5. SONUÇLAR

Bu çalışmanın temel amacı, hidrojen-doğalgaz karışımının yanma performansını ve emisyon seviyelerini analiz ederek hidrojenin yanma sistemlerine entegrasyonunu optimize etmektir. Çalışma kapsamında:

- Silindirik bir yanma odasında hidrojen yüzdesinin (hacmen %0, %20, %40, %60 ve %80 H_2) yanma sıcaklığı ve NOx emisyonları üzerindeki etkisi incelenmiştir.
- Farklı hidrojen oranları için sıcaklık dağılımı, yanma verimliliği ve emisyon seviyeleri karşılaştırılmıştır.
- CFD analizleri kullanılarak türbülans ve akış karakteristikleri değerlendirilmiştir.
- Elde edilen sonuçlar doğrultusunda hidrojenin doğalgazla birlikte kullanımına yönelik optimizasyon önerileri sunulmuştur.

Sonuç olarak, bu çalışma, hidrojen-doğalgaz karışımlı sistemlerin optimizasyonuna yönelik gelecekteki araştırmalara rehberlik etmektedir.

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TIBBİ BİTKİLERDE DROG HAZIRLAMADA ETKEN MADDE KAYIPLARI VE DEĞİŞİMLERİ: NEDENLER VE ÖNLEME STRATEJİLERİ

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ÖZET

Tıbbi bitkilerde drog hazırlama süreci, farmasötik kalite, biyolojik etkinlik ve güvenlik açısından kritik öneme sahiptir. Ancak hasattan depolamaya kadar uzanan zincirde; genetik varyasyon, çevresel koşullar, hasat ve taşıma uygulamaları, kurutma, öğütme, ekstraksiyon, ambalajlama ve depolama gibi birçok faktör, etken maddelerin niceliksel kaybına veya kimyasal değişimine yol açmaktadır. Yanlış fenolojik dönemde hasat, yüksek sıcaklıkta kurutma, uygunsuz partikül boyutu, uzun süreli ekstraksiyon ve yetersiz ambalajlama, başlıca kayıp nedenleri arasında yer almaktadır. Bu kayıplar yalnızca ürünün terapötik etkinliğini değil; aynı zamanda raf ömrünü, standardizasyonunu ve ticari değerini de olumsuz etkilemektedir. Literatürden elde edilen veriler, kontrollü sıcaklık ve nem yönetimi, uygun parçalama boyutu, modern ekstraksiyon teknikleri (ultrasonik, mikrodalga, süperkritik CO_2), inert atmosferde ambalajlama ve GMP/GACP ilkelerinin uygulanmasıyla etken madde stabilitesinin büyük ölçüde korunabileceğini göstermektedir. Dolayısıyla, bilimsel temelli kalite kontrol protokolleri ve sürdürülebilir üretim yaklaşımları, tıbbi bitkilerin güvenli ve etkili şekilde kullanılabilmesi için kaçınılmazdır.

Anahtar Kelimeler: tıbbi bitkiler, drog hazırlama, etken madde kaybı, kalite kontrol, GACP, GMP

ACTIVE COMPOUND LOSSES AND ALTERATIONS IN DRUG PREPARATION FROM MEDICINAL PLANTS: CAUSES AND PREVENTION STRATEGIES

ABSTRACT

The drug preparation process in medicinal plants is critically important in terms of pharmaceutical quality, biological efficacy, and safety. However, numerous factors in the chain from harvest to storage—including genetic variation, environmental conditions, harvesting and transportation practices, drying, grinding, extraction, packaging, and storage—can lead to quantitative loss or chemical alteration of active compounds. Major causes of such losses include harvesting at the wrong phenological stage, drying at high temperatures, inappropriate particle size, prolonged extraction, and inadequate packaging. These losses not only compromise the therapeutic efficacy of the product but also negatively affect its shelf life, standardization, and commercial value. Data from the literature indicate that controlling temperature and humidity, optimizing particle size, employing modern extraction techniques (ultrasonic, microwave, supercritical CO_2), packaging in an inert atmosphere, and implementing GMP/GACP principles can significantly preserve active compound stability. Therefore, scientifically grounded quality control protocols and sustainable production approaches are indispensable for the safe and effective use of medicinal plants.

Keywords: medicinal plants, drug preparation, active compound loss, quality control, GACP, GMP

Giriş

Tıbbi bitkiler insanlık tarihi boyunca hastalıkların önlenmesi ve tedavisinde vazgeçilmez kaynaklardan biri olmuştur. Arkeolojik ve etnobotanik bulgular, bitkisel drogların Mezopotamya, Antik Mısır, Hint ve Çin uygarlıklarında sistematik biçimde kullanıldığını göstermektedir. Modern farmakoloji ve fitoterapi de temellerini bu kadim uygulamalardan almıştır. Günümüzde Dünya Sağlık Örgütü'nün (WHO) verilerine göre dünya nüfusunun yaklaşık %80'i temel sağlık hizmetlerinde hâlâ bitkisel kaynaklı tedavi yöntemlerinden yararlanmaktadır. Küresel ölçekte doğal ürün ve fitoterapi pazarının 2030'a kadar 300 milyar Amerikan dolarını aşması beklenmektedir. Bu hızlı büyüme, **drog hazırlama** sürecinin bilimsel temellerle yönetilmesini zorunlu kılmaktadır. Günümüzde farmakognozi ve fitoterapi bilimlerinin gelişmesiyle bitkisel ilaçların, fonksiyonel gıdaların ve nutrasötik ürünlerin endüstriyel üretimi büyük bir ivme kazanmıştır. Dünya Sağlık Örgütü (WHO) verilerine göre dünya nüfusunun %80'i sağlık hizmetlerinde hâlâ bitkisel ürünlerden yararlanmaktadır. Bu geniş kullanım alanı, drog hazırlama sürecinin hem sağlık hem de ekonomik boyutta kritik önemini ortaya koymaktadır (Prasad ve ark., 2021)

Farmakognozi terminolojisinde **drog**, tıbbi amaçla kullanılan, çoğunlukla kurutulmuş bitki kısımlarını (yaprak, çiçek, kök, kabuk, meyve, tohum vb.) ifade eder. Drog, bitkinin tedavi edici gücünü belirleyen **sekonder metabolitleri** (alkaloidler, flavonoidler, terpenoidler, fenolik asitler vb.) içeren hammadde olup; bitkisel ilaçlar, fonksiyonel gıdalar, kozmesötikler ve nutrasötiklerin üretiminde doğrudan rol oynar (Brown ve ark., 2017) Bu nedenle drog hazırlama, **etkin madde stabilitesini koruyan, kontaminasyonu önleyen ve standardizasyon sağlayan** temel aşamadır. Drog hazırlama, sadece geleneksel bilgiye dayalı bir süreç değildir; modern analitik kimya, farmasötik teknoloji, gıda güvenliği ve sürdürülebilir tarım ilkelerini birleştiren çok disiplinli bir üretim hattıdır. Bu süreç; **hasat, kurutma, öğütme, eleme, standardizasyon, kalite kontrol, ambalajlama ve izlenebilirlik** gibi birbirini tamamlayan aşamaları kapsar. Her aşama, son ürünün farmasötik kalitesini ve biyolojik etkinliğini doğrudan etkiler. Ayrıca bu süreçlerde (hasat, kurutma, parçalama, öğütme, depolama aşamalarında) bitkinin içerdiği etken maddelerin (biyoaktif bileşikler) miktarı ve yapısı önemli ölçüde değişebilir. Bu değişimler, drog kalitesini, farmakolojik etkinliğini ve raf ömrünü doğrudan etkiler. İyi bir drog üreticisi her şeyden önce etken madde değişimi (varyabiliteyi) çok iyi bilmesi gerekir. Tıbbi bitkilerde morfogenetik varyabilite, yani bitkinin genetik yapısı ile gelişim evresine bağlı morfolojik değişkenlik, drog kalitesini ve etken madde miktarını doğrudan etkileyen temel biyolojik faktörlerden biridir. Drog hazırlama sürecinde bu özellik iyi anlaşılmazsa etken madde kayıpları ve standardizasyon sorunları ortaya çıkabilir. Ontogenetik varyabilite, bitkinin bireysel gelişim evrelerine (ontogeni) bağlı olarak kimyasal bileşimde ve etken madde (biyoaktif bileşik) miktarında ortaya çıkan değişimleri ifade eder. Drog kalitesi, farmakolojik etkinlik ve standardizasyon açısından bu varyabilitenin bilinmesi hayati önem taşır. Bitkiler, ışık–karanlık döngüsüne (fotoperiyot) ve gün içindeki sıcaklık-nem değişimlerine bağlı olarak biyoaktif bileşiklerinin miktarını gün boyunca dalgalandırır. Bu durum tıbbi bitkilerde diurnal (günlük) varyabilite olarak adlandırılır ve drog hazırlama sürecinde dikkate alınması gereken önemli bir faktördür.

Tıbbi bitkilerde etken madde profili; bitkinin genetik yapısı, çevresel koşullar, hasat zamanı ve yöntemi, kurutma, parçalama, ekstraksiyon, ambalajlama ve depolama süreçlerinden yoğun biçimde etkilenir. Örneğin, uçucu yağ bileşenleri ışık, sıcaklık ve oksijen varlığında kolayca bozulabilir; fenolik bileşikler ise oksidatif enzimler tarafından parçalanabilir. Bu tür değişimler sadece miktar azalmalarına değil, aynı zamanda bileşenlerin kimyasal yapılarında dönüşümlere (hidroliz, oksidasyon, izomerizasyon gibi) yol açabilir. Tıbbi bitkilerde drog hazırlama zinciri (hasat → kurutma → öğütme/eleme → ekstraksiyon → ambalajlama → depolama) boyunca

sekonder metabolitlerde (alkaloidler, flavonoidler, terpenoidler, fenolik asitler vb.) niceliksel azalma ve/veya kimyasal dönüşümler meydana gelebilir. Bu değişimler ürünün terapötik etkisini, raf ömrünü ve mevzuata uygunluğunu doğrudan etkiler; bu nedenle farmakope/guideline çerçevesinde kalite-süreç kontrolü zorunludur

Bu makalede amaç; drog hazırlama zincirinde etken madde kayıplarına neden olan faktörleri ve mekanizmaları kapsamlı biçimde listelemek; her bir aşamada hangi önlemler alınabileceğini literatür desteğiyle ortaya koymaktır. Böylece, doğal ürün endüstrisinde kalite güvence standartlarının geliştirilmesine bilimsel bir katkı sunulması hedeflenmektedir.

2. Etken Madde Kayıplarına Neden Olan Faktörler

2.1 Bitkisel ve Genetik Faktörler

Tür ve Varyete Farklılıkları

Her bitki türü ve hatta aynı türün farklı varyeteleri, sekonder metabolit profilleri açısından önemli farklılıklar gösterebilir.

- **Mentha spp. (nane türleri):** *Mentha piperita*'da mentol baskınken, *Mentha spicata*'da carvone yoğunluktadır (Baser & Buchbauer, 2010). Bu, aynı cins içinde bile farklı uçucu yağ profillerine yol açar.
- **Hypericum perforatum (sarı kantaron):** Farklı ekotipler arasında hiperisin ve hiperforin düzeylerinde 3–4 kat farklılık rapor edilmiştir (Hammer et al., 2007; *Brown ve ark., 2017).*

Bu nedenle drog standardizasyonunda tür-varyete ayrımı kritik önemdedir.

Fenolojik Evre (Gelişim Dönemi)

Bitkinin gelişim evresi, metabolit yoğunluğunu belirleyen en güçlü faktörlerden biridir.

- **Matricaria chamomilla (papatya):** Apigenin-glikozitler tam çiçeklenme döneminde maksimum düzeydedir (Srivastava et al., 2010).
- **Rosmarinus officinalis (biberiye):** Rozmarinik asit ve karnosik asit miktarları çiçeklenme döneminde en yüksek düzeye çıkar.
- **Digitalis purpurea (yüksük otu):** Kardiyak glikozitler, yaprak olgunlaşma sürecinde artış gösterir.

Yanlış fenolojik dönemde yapılan hasat, etkin madde kaybına yol açabilir.

Bitkinin Kullanılan Kısmı

Etken madde konsantrasyonu, bitkinin farklı organlarında büyük değişiklikler gösterebilir.

- **Cinchona spp. (kınakına):** Kinolin alkaloidleri (kinin) kabukta yoğunlaşırken, yaprak ve gövdede oldukça düşüktür.
- **Papaver somniferum (haşhaş):** Morfin ve türevleri kapsülde yüksekken, yaprak ve gövdede yok denecek kadar azdır.
- **Foeniculum vulgare (rezene):** Anetol esas olarak tohumda birikir, yapraklarda ise eser düzeydedir.

Bu nedenle farmakopeler (örneğin Avrupa Farmakopesi) drog tanımında bitkinin hangi kısmının kullanılacağını açıkça belirtir.

Genetik Çeşitlilik ve Ekotipler

Aynı türün farklı coğrafi bölgelerde yetişen ekotipleri, genetik adaptasyon nedeniyle farklı metabolit profilleri geliştirebilir.

- **Thymus vulgaris (kekik):** "Kemotip" kavramının tipik örneğidir. Bazı populasyonlarda timol baskınken, bazılarında karvakrol veya linalol ön plandadır (Skoula & Harborne, 2002).
- **Artemisia annua (tatlı pelin):** Artemisinin miktarı ekotipler arasında %0,1–1,5 arası değişebilir. Bu farklılık, sıtma tedavisinde kullanılan preparatların standardizasyonunda önemli bir sorun oluşturur (Ferreira & Janick, 1996).

Sekonder Metabolit Biyosentezinde Genetik Kontrol

Sekonder metabolit üretimi; genetik olarak kontrol edilen enzim sistemlerine bağlıdır.

- Flavonoid biyosentezinde **chalcone synthase (CHS)**,
- Alkaloid biyosentezinde **strictosidine synthase**,
- Terpen biyosentezinde **terpene synthase (TPS)** genleri kritik rol oynar.

Bu genlerdeki polimorfizmler, aynı tür içinde bile metabolit çeşitliliğine neden olabilir (Pichersky & Lewinsohn, 2011; Wang ve ark., 2023).

3. Çevresel ve Agroekolojik Faktörler

Tıbbi bitkilerde sekonder metabolitlerin (ör. alkaloidler, fenolik bileşikler, flavonoidler, uçucu yağlar) miktarı ve bileşimi yalnızca genetik farklılıklardan değil, aynı zamanda çevresel ve agroekolojik koşullardan da yoğun biçimde etkilenir. Drog hazırlama sürecinde etken madde kayıpları ve değişimlerinin önemli bir kısmı, bu koşulların doğrudan veya dolaylı etkilerinden kaynaklanmaktadır.

3.1 İklim Koşulları

- **Sıcaklık:** Aşırı sıcaklıklar, uçucu yağ bileşenlerinin buharlaşmasına ve fenolik bileşiklerde oksidatif kayıplara neden olabilir. Örneğin, *Mentha piperita*'da mentol oranı ılıman koşullarda yüksek, yüksek sıcaklıklarda düşük bulunmuştur (Kizil et al., 2010).
- **Işık Şiddeti ve Fotoperiyot:** Yüksek ışık şiddeti flavonoid ve fenolik sentezini artırabilir; fakat uzun süreli yoğun ışık, özellikle antosiyaninlerde bozulmalara yol açabilir. *Hypericum perforatum* bitkisinde hiperisin içeriği güneşlenme süresine bağlı olarak artış göstermektedir (Walker et al., 2001).
- **Yağış ve Nem:** Yüksek nem koşulları bitki üzerinde mikrobiyal yük riskini artırırken, kuraklık stresi bazı türlerde savunma metabolitlerini (örn. fenolikler, terpenler) artırabilir. *Rosmarinus officinalis*'te kurak koşullar, rozmarinik asit düzeyini artırmıştır (Petropoulos et al., 2019).

3.2 Toprak Özellikleri

- **pH ve Mineral İçeriği:** Toprak pH'ı, sekonder metabolit sentezinde görevli enzimlerin aktivitesini etkileyebilir. Örneğin, *Camellia sinensis* (çay) bitkisinde düşük pH koşulları kateşin oranlarını artırmıştır (Ahmed et al., 2019).
- **Besin Elementleri:** Azot gübrelemesinin fenolik bileşik düzeylerini düşürdüğü, fosfor ve potasyumun ise uçucu yağ sentezini desteklediği rapor edilmiştir. *Ocimum basilicum*

(fesleğen)'de azotlu gübrelemenin linalool içeriğini artırdığı, ancak öjenol seviyelerini azalttığı gösterilmiştir (Sifola & Barbieri, 2006).

3.3 Abiyotik Stres Faktörleri

- **Kuraklık:** Su stresi bitkilerde savunma metabolitlerini artırabilir. *Artemisia annua*'da artemisinin içeriği orta derecede su stresinde yükselmiştir (Marchese et al., 2018).
- **Tuzluluk:** Tuzlu koşullar, bazı fenolik bileşiklerin sentezini tetikleyebilir; *Glycyrrhiza glabra* (meyan kökü)'nda glisirizin miktarı tuzlulukla artış göstermiştir (Gupta & Huang, 2014).
- **UV Radyasyonu:** UV-B ışınları flavonoid üretimini artırarak bitkinin savunma mekanizmasını güçlendirir; *Petroselinum crispum* (maydanoz)'da UV maruziyeti ile flavonoid düzeylerinde artış saptanmıştır (Rozema et al., 2002).

3.4 Agroekolojik Uygulamalar

- **Ekolojik Bölge ve Rakım:** Rakım arttıkça bazı metabolitlerde (ör. antosiyaninler, fenolik asitler) artış rapor edilmiştir. *Thymus vulgaris*'te yüksek rakımlarda timol ve karvakrol oranı artmıştır (Bahreininejad et al., 2013).
- **Organik Tarım Uygulamaları:** Kimyasal gübre yerine organik gübre kullanımı, sekonder metabolit düzeylerinde farklılık yaratabilir. *Allium sativum* (sarımsak)'ta organik tarım uygulamalarıyla allicin içeriğinin daha yüksek olduğu bildirilmiştir (Amagase, 2006).

Çevresel ve agroekolojik faktörler, tıbbi bitkilerde etken madde içeriğini ve stabilitesini doğrudan belirler. Sıcaklık, ışık, yağış, toprak özellikleri, stres faktörleri ve agroekolojik uygulamalar; metabolit profillerinde farklılıklara yol açarak drog kalitesini doğrudan etkiler. Bu nedenle drog hazırlama sürecinde **GACP (Good Agricultural and Collection Practices)** ilkeleri doğrultusunda ekolojik ve çevresel koşulların kayıt altına alınması, standardizasyon ve kalite güvence açısından zorunludur.

4. Hasat ve Taşıma

Tıbbi bitkilerde drog kalitesini belirleyen en kritik aşamalardan biri **hasat ve taşıma süreci**dir. Bu aşamada yapılan hatalar, bitkinin içerdiği sekonder metabolitlerde hızlı kayıplara, kimyasal dönüşümlere ve mikrobiyal kontaminasyona yol açabilir. WHO ve EMA tarafından yayımlanan **GACP (Good Agricultural and Collection Practices)** kılavuzları, hasat ve taşıma adımlarının standardizasyonunu zorunlu kılmaktadır (WHO, 2023; EMA, 2022).

4.1 Hasat Zamanı

- **Fenolojik Dönem:** Bitkinin gelişim evresi, etken madde miktarında belirleyici faktördür. Örneğin:
  - *Matricaria chamomilla* (papatya)'da apigenin-glikozitleri çiçeklenmenin tam ortasında maksimum düzeydedir (Srivastava et al., 2010).
  - *Mentha piperita* (nane)'da mentol oranı çiçeklenme öncesi yüksektir (Kizil et al., 2010).
  - *Hypericum perforatum* (sarı kantaron)'da hiperisin üretimi çiçeklenme döneminde zirveye ulaşır (Walker et al., 2001).
- **Gün İçi Zamanlama:** Sabah erken saatlerde uçucu yağ bileşenleri genellikle daha yoğun olur. Öğle sıcağı veya akşamüstü toplama, uçucu bileşiklerde kayba neden olabilir.

4.2 Hasat Yöntemi ve Mekanik Zedelenme

- **Mekanik Hasar:** Biçme ve kesme sırasında meydana gelen hücre zedelenmeleri, **polifenol oksidaz (PPO)** ve **peroksidaz (POD)** gibi enzimleri aktive ederek fenolik bileşiklerde oksidatif kayba neden olur (Tilley et al., 2023).
- **Ekipman Seçimi:** Paslanmaz çelikten veya inert materyallerden üretilmiş kesici aletler tercih edilmelidir. Paslı aletler ağır metal bulaşmasına ve fenolik oksidasyonuna yol açabilir.
- **Hijyen:** Hasat sırasında toprak, taş, böcek parçaları gibi yabancı materyallerin bulaşmasını önlemek için temiz alanlarda çalışılmalıdır.

4.3 Hasattan Sonra Taşıma Koşulları

- **Zaman Faktörü:** Hasattan sonra işleme (kurutma veya ekstraksiyon) noktasına hızlı taşınma çok önemlidir. Gecikme, özellikle yüksek nem koşullarında mikrobiyal gelişimi hızlandırır.
- **Sıcaklık ve Nem:** Taşıma sırasında sıcaklık ve nemin yüksek olması, uçucu yağların buharlaşmasına ve biyokimyasal bozunmalara yol açar. *Ocimum basilicum* (fesleğen)'de yapılan çalışmalar, yüksek sıcaklıkta taşınan örneklerde linalool kaybının %15'e kadar çıktığını göstermektedir (Sifola & Barbieri, 2006).
- **Ambalajlama:** Hasat edilen materyal, hava geçirgen torbalarda (keten, jüt vb.) taşınmalıdır. Plastik torbalarda taşınma, terleme ve küf gelişimi riskini artırır.

4.4 Mikrobiyal ve Kimyasal Riskler

- **Mikrobiyal Kontaminasyon:** Yüksek nem ve sıcaklıkta bekletilen bitkilerde küf ve maya gelişimi hızlıdır. Bu durum aflatoksin oluşumuna kadar varabilen riskler taşır (USP <561>, 2023).
- **Kimyasal Kirlilik:** Taşıma sırasında kullanılan araçlardan kaynaklanabilecek yağ, yakıt veya pestisit bulaşmaları etken madde kalitesini düşürebilir.

4.5 Örnek Çalışmalar

- *Artemisia annua* (tatlı pelin)'da yapılan bir çalışmada, hasattan sonra 24 saat bekletilen örneklerde artemisinin içeriğinde %12 kayıp saptanmıştır (Marchese et al., 2018).
- *Ginkgo biloba* yapraklarında hızlı taşınan örneklerde ginkgoflavon içeriği korunurken, 48 saat açık ortamda bekletilenlerde %20'ye varan azalma rapor edilmiştir (Li et al., 2021).

Hasat ve taşıma aşamaları, tıbbi bitkilerde etken madde stabilitesi için kritik kontrol noktalarıdır. Uygun fenolojik dönemde, doğru ekipmanla, hijyenik koşullarda ve hızlı taşımayla gerçekleştirilen hasat süreci; etken madde kayıplarını minimize eder. GACP kılavuzları, bu süreçlerin kayıt altına alınmasını ve izlenebilirliğini zorunlu kılarak farmasötik kaliteyi güvence altına almaktadır.

5. Kurutma ve Nem Yönetimi

Kurutma, drog hazırlama zincirinde **etken maddelerin stabilitesini korumak** açısından en kritik aşamalardan biridir. Yanlış kurutma rejimleri, hem **biyokimyasal bozunmalara** hem de **mikrobiyal kontaminasyona** yol açabilmektedir.

- **Kurutma Sıcaklığı ve Süresi:**
  - 60 °C üzeri sıcaklıklarda uçucu yağlar ve ısıya duyarlı vitaminler (askorbik asit) hızla parçalanır.

- *Matricaria chamomilla* çiçeklerinde 45 °C'nin üzerinde apigenin türevlerinde kayıp bildirilmiştir (Bal et al., 2019).

- **Doğal Kurutma:** Gölge ve hava sirkülasyonu kullanılarak düşük maliyetle uygulanır, ancak nem ve mikrobiyal yük riski yüksektir.

- **Yapay Kurutma:** Kontrollü sıcaklık ve hava akımı ile kısa sürede nem azaltılır, mikrobiyal yük düşürülür.

- **Alternatif Yöntemler:**

- Mikrodalga ve ultrases destekli kurutma, süreyi kısaltarak polifenol kayıplarını azaltır (Saini et al., 2018).

- **Nem Aktivitesi (aw):** aw > 0.7 olduğunda küf ve maya gelişimi hızlanır. İdeal değer aw ≤ 0.6–0.7 aralığıdır (Liu et al., 2022).

Özetle: Kurutma, nem kaybı ve bileşik korunumu arasında hassas bir denge gerektirir.

6. Öğütme, Parçalama ve Ekstraksiyon

6.1 Öğütme ve Parçalama

Öğütme ve parçalama, bitkisel drogun işlenmesinde **etken maddelerin serbest hale getirilmesi** ve **yüzey alanının artırılması** için zorunlu aşamalardır. Ancak bu işlemler, uygun yapılmadığında **oksidatif kayıplara** ve **ısıl bozunmalara** neden olabilir.

6.1.1 Partikül Boyutu

- **Çok ince öğütme:** Yüzey alanını artırarak oksijen ve ışığa maruziyeti artırır; bu durum fenolik bileşiklerde oksidasyonu hızlandırır.

- **Çok iri parçalama:** Ekstraksiyon sırasında çözünürlük ve difüzyon hızını düşürür.

- **Optimum boyut:** Genellikle 0.5–1 mm arası partikül boyutu, ekstraksiyon verimi ile stabilite arasında denge sağlar (Rodríguez-Pérez et al., 2020).

6.1.2 Mekanik ve Termal Etkiler

- **Isınma:** Yüksek devirli değirmenlerde sürtünme ısısı ortaya çıkar, bu da uçucu yağların buharlaşmasına yol açar. Örneğin, *Cinnamomum verum* (tarçın)'da öğütme sırasında sinnamaldehit kaybı rapor edilmiştir (Bal et al., 2019).

- **Metal kontaminasyonu:** Demir, bakır gibi iyonlar fenoliklerle reaksiyona girerek renk değişimi ve etkinlik kaybına neden olabilir. Paslanmaz çelik veya seramik değirmenler tercih edilmelidir.

6.2 Ekstraksiyon

Ekstraksiyon, etken maddelerin bitki dokusundan çözücüye aktarılması işlemidir. Bu aşama, **drogun farmasötik değerini** belirleyen en önemli basamaklardan biridir.

6.2.1 Klasik Ekstraksiyon Yöntemleri

- **Maserasyon:** Oda sıcaklığında çözücü içinde bekletme. Termolabil bileşikler için uygundur, ancak uzun süre gerektirir.

- **Perkolasyon:** Sürekli çözücü akışıyla ekstraksiyon yapılır, daha verimli fakat yine uzun zaman alıcıdır.

- **Kaynatma (Dekoksiyon):** Isıya dayanıklı bileşikler için kullanılır; ancak uçucu bileşiklerde kayıplara yol açar.

6.2.2 Modern Ekstraksiyon Teknikleri

- **Ultrasonik ekstraksiyon (UAE):** Ses dalgaları hücre duvarlarını parçalayarak çözücü penetrasyonunu artırır. Fenoliklerde verimi yükseltir ve süreci kısaltır (Saini et al., 2018).
- **Mikrodalga destekli ekstraksiyon (MAE):** Hücre içi ısıtma ile bileşenlerin hızlı çözünmesini sağlar, ekstraksiyon süresini büyük ölçüde azaltır.
- **Süperkritik CO_2 ekstraksiyonu (SFE):** Özellikle uçucu yağlarda tercih edilir. Çözücü kalıntısı bırakmaz ve düşük sıcaklıkta gerçekleştiği için termolabil bileşiklerde etkinliği korur (Li et al., 2021).

6.2.3 Ekstraksiyon Parametreleri

- **Sıcaklık:** Yüksek sıcaklık ekstraksiyon hızını artırır, fakat fenolik asitler ve antosiyaninler gibi termolabil bileşenleri bozabilir.
- **Süre:** Uzun süreli işlem hidroliz ve izomerizasyona yol açar.
- **Çözücü Seçimi:**
  - Su: Suda çözünen polifenoller için,
  - Etanol: Flavonoidler ve alkaloidler için,
  - Hidroalkolik karışımlar: Çoğu fenolik bileşik için optimum sonuç verir.

6.3 Örnek Çalışmalar

- *Artemisia annua*'da ultrasonik ekstraksiyon, klasik maserasyona göre artemisinin verimini %35 artırmıştır (Marchese et al., 2018).
- *Ginkgo biloba* yapraklarında mikrodalga destekli ekstraksiyon, ginkgoflavon glikozitlerin korunmasında geleneksel yöntemlerden daha etkili bulunmuştur (Zhou et al., 2017).
- *Ocimum basilicum* uçucu yağlarında süperkritik CO_2 ekstraksiyonu ile linalool kaybı minimum düzeyde tutulmuştur (Ebadi et al., 2016).

Öğütme, parçalama ve ekstraksiyon süreçleri, **drog kalitesini belirleyen kritik noktalar**dır. Aşırı öğütme ve uygunsuz ekstraksiyon parametreleri, etken madde kayıplarını artırırken; modern teknolojilerin (UAE, MAE, SFE) uygulanması kaliteyi artırmakta ve süreci kısaltmaktadır.

7. Ambalajlama ve Depolama

Tıbbi bitkilerde drog hazırlama sürecinin son halkaları olan **ambalajlama ve depolama**, ürünün **raf ömrü, biyolojik etkinliği ve güvenliği** açısından kritik öneme sahiptir. Hasat, kurutma ve ekstraksiyon aşamalarında elde edilen kalite, uygun olmayan ambalaj ve depolama koşullarında hızla kaybolabilir. Dünya Sağlık Örgütü (WHO), Avrupa Farmakopesi (Ph. Eur.) ve Amerika Birleşik Devletleri Farmakopesi (USP) bu aşamalar için kalite standartları geliştirmiştir (WHO, 2023; USP <561>, 2023).

7.1 Ambalajlama

7.1.1 Işık ve Oksijen Bariyeri

- **Işık duyarlılığı:** Antosiyaninler, karotenoidler, flavonoidler ve uçucu yağlar ışığa karşı oldukça hassastır. Örneğin, *Hypericum perforatum*'daki hiperisin ışıkta hızla parçalanır (Walker et al., 2001).
- **Oksijen etkisi:** Fenolik bileşikler oksijen varlığında oksidatif bozunmaya uğrar. Özellikle uçucu yağlarda oksidasyon, etkinlik kaybı ve toksik bileşik oluşumuna yol açabilir.

Çözüm:

- Koyu renkli cam şişeler, alüminyum folyo ambalajlar veya vakumlu torbalar kullanılmalıdır.
- Azot (N_2) veya argon (Ar) gibi inert gazlarla paketleme, oksijen maruziyetini azaltır.

7.1.2 Ambalaj Materyali

- **Plastik materyaller:** PVC veya PE ambalajlar uçucu yağ bileşikleri ile etkileşime girerek adsorpsiyon veya göç riskine sahiptir.
- **Metal ve cam:** Kimyasal olarak inerttir ve ışık/oksijen bariyeri sağlar.

7.2 Depolama

7.2.1 Sıcaklık ve Nem

- **Sıcaklık:** 15–25 °C arası sabit sıcaklık önerilmektedir. Yüksek sıcaklıkta depolama, uçucu yağların buharlaşmasına ve fenolik bileşiklerde oksidasyona neden olur.
- **Nem:** Bağıl nemin %40–50 seviyesinde tutulması idealdir. Yüksek nem, mikrobiyal kontaminasyon (küf, maya) riskini artırır.

7.2.2 Süre ve Raf Ömrü

- Raf ömrü, drog tipine göre değişmekle birlikte genellikle **1–2 yıl** ile sınırlandırılmaktadır.
- Uçucu yağ içeren bitkiler (ör. nane, kekik, fesleğen) 12 ayı aşan depolamalarda %15–20 düzeyinde kayıp gösterebilir (Ebadi et al., 2016).

7.2.3 Mikrobiyal ve Kimyasal Güvenlik

- Uygun olmayan depolama koşullarında **aflatoksin** oluşumu en ciddi risklerden biridir. USP <561> ve Ph. Eur., aflatoksin B1 için ≤5 ppb, toplam aflatoksin için ≤20 ppb sınırını belirlemiştir.
- Pestisit ve ağır metal kalıntıları da depolama sırasında migrasyon yoluyla artabilir.

7.3 Örnek Çalışmalar

- *Ocimum basilicum* (fesleğen)'de 12 aylık depolama sonunda linalool içeriğinde %20 azalma gözlenmiştir (Ebadi et al., 2016).
- *Mentha piperita*'da vakumlu ambalajlama ile mentol içeriğinin 6 ay boyunca korunduğu, ancak açık ortamda depolamada %30'a varan kayıp olduğu rapor edilmiştir (Kizil et al., 2010).
- *Curcuma longa* (zerdeçal)'da polifenolik kurkuminoidlerin nemli koşullarda 3 ayda %15 azaldığı bildirilmiştir (Syed et al., 2015).

Ambalajlama ve depolama, drogların **stabilitesi ve güvenliği** için son derece kritik basamaklardır. Yanlış koşullar, sadece biyolojik etkinliği azaltmakla kalmaz, aynı zamanda halk sağlığı için risk oluşturabilecek mikotoksin ve bozulma ürünlerinin oluşmasına da neden olur.

En iyi uygulamalar:

- Işık geçirmez, inert, oksijen bariyerli ambalajlar,
- İnert gaz atmosferinde paketleme,
- Kontrollü sıcaklık ve nemde depolama,
- Lot bazlı izlenebilirlik ve düzenli kalite analizleri.

Tablo 3. Depolama Faktörleri – Risk – Etken Maddeye Etkisi – Önleme Stratejileri

Depolama Faktörü	Risk / Problem	Etken Maddeye Etkisi	Önleme Stratejisi
Sıcaklık	Yüksek sıcaklık uçucu bileşiklerin buharlaşmasına, fenoliklerin oksidasyonuna yol açar	Mentol, timol, linalool gibi uçucularda %15–30 kayıp; C vitamini bozulması	15–25 °C sabit sıcaklık, sıcaklık dalgalanmalarını önleyici depolar
Bağıl Nem	Yüksek nem → küf/maya gelişimi, hidroliz reaksiyonları	Kurkuminoidler, glikozitler ve fenoliklerde bozulma; aflatoksin riski	%40–50 bağıl nem, desikantlar, nem bariyerli ambalaj
Işık (UV/Vis)	Fotooksidasyon ve renk bozulması	Antosiyanin, karotenoid, hiperisin gibi ışığa duyarlı bileşiklerde parçalanma	Koyu cam şişe, ışık geçirmez ambalaj, alüminyum folyo kaplama
Oksijen	Oksidatif bozunma, peroksit oluşumu	Fenoliklerin polimerizasyonu, uçucularda peroksit ve aldehit oluşumu	Vakumlu paketleme, azot/argon atmosferinde ambalajlama
Ambalaj Materyali	PVC/PE ambalajlarda bileşik adsorpsiyonu veya migrasyonu	Uçucu yağlarda kayıp, pestisit/kimyasal bulaşma	Cam, metal veya inert polimer ambalaj kullanımı
Depolama Süresi	Uzun süre → oksidatif bozulma, biyolojik aktivite azalması	12 ay sonra uçucularda %15–20; fenoliklerde %10–15 kayıp	Raf ömrünü 12–24 ay ile sınırlama, parti-parti kalite analizleri
Mikrobiyal Kontaminasyon	Uygunsuz koşullarda küf gelişimi, aflatoksin üretimi	Farmasötik kalite kaybı, toksisite riski	USP <561> limitlerine uygunluk, düzenli mikrobiyolojik analiz, hijyenik depolama alanı

Tablo 4. Ambalajlama ve Depolama Sürecinde Etken Madde Kayıpları ve Önleme Stratejileri

Faktör	Risk / Problem	Etken Maddeye Etkisi	Önleme Stratejisi
Işık (UV, görünür)	Fotooksidasyon, renk bozulması	Antosiyaninler, karotenoidler, hiperisin gibi bileşiklerde parçalanma	Koyu cam, alüminyum folyo, ışık geçirmez ambalaj
Oksijen	Oksidatif bozunma	Fenoliklerde polimerleşme, uçucu yağlarda peroksit oluşumu	Vakumlu paketleme, inert atmosfer (N_2/Ar)
Nem	Küf, maya gelişimi; hidroliz reaksiyonları	Kurkuminoidler, fenolikler ve glikozitlerde parçalanma	%40–50 bağıl nem kontrolü, desikant kullanımı, nem bariyerli ambalaj
Sıcaklık	Uçucu bileşiklerin buharlaşması, fenolik oksidasyonu	Mentol, timol, linalool, askorbik asit kaybı	15–25 °C sabit sıcaklıkta depolama, sıcaklık dalgalanmasını önleme
Ambalaj Materyali	PVC/PE ile uçucu bileşik etkileşimi, migrasyon riski	Uçucu yağlarda adsorpsiyon ve kayıp	Cam, metal veya inert polimer kullanımı
Depolama Süresi	Uzun sürede oksidasyon ve biyolojik aktivite azalması	Linalool (%20), mentol (%30), kurkuminoidler (%15) kaybı	Raf ömrünün 12–24 ay ile sınırlandırılması, periyodik kalite analizleri
Mikrobiyal Kontaminasyon	Uygun olmayan nem ve sıcaklıkta küf gelişimi, aflatoksin riski	Halk sağlığı açısından toksisite, farmasötik kalite kaybı	USP <561> limitlerine uygunluk, mikrobiyolojik testler, temiz depolama alanı

9. Sonuç, Değerlendirme ve Öneriler

9.1 Sonuç

Bu çalışma, tıbbi bitkilerde drog hazırlama sürecinde **etken madde kayıplarının** ortaya çıkış nedenlerini, biyokimyasal mekanizmalarını ve önlenmesine yönelik stratejileri kapsamlı biçimde ele almıştır. Hasat, taşıma, kurutma, öğütme, ekstraksiyon, ambalajlama ve depolama aşamalarında yapılan hataların; fenolik bileşiklerde oksidatif kayıplara, uçucu yağlarda buharlaşmaya, glikozitlerde hidrolize ve mikrobiyal kontaminasyona yol açtığı ortaya konmuştur. Özellikle **ısı, ışık, nem ve oksijen** gibi çevresel faktörlerin kontrol edilmediği durumlarda, drogun farmasötik kalitesinin kısa sürede azaldığı görülmektedir.

9.2 Değerlendirme

- **Hasat ve Taşıma:** Yanlış fenolojik dönemde yapılan hasat, mekanik zedelenme ve gecikmiş taşıma, etken madde kayıplarını artırmaktadır. GACP uygulamaları bu aşamada kritik öneme sahiptir.
- **Kurutma ve Nem Yönetimi:** Yüksek sıcaklık ve uzun süreli kurutma, fenolik ve uçucu bileşiklerde ciddi kayıplara yol açmaktadır. Kontrollü sıcaklık ve nem yönetimi, kaliteyi koruyan en önemli parametredir.
- **Öğütme ve Ekstraksiyon:** Çok ince öğütme oksidasyonu hızlandırmakta; yanlış ekstraksiyon parametreleri termolabil bileşiklerin kaybına neden olmaktadır. Modern teknikler (ultrasonik, mikrodalga, süperkritik CO_2) kaliteyi artırmaktadır.
- **Ambalajlama ve Depolama:** Uygun olmayan ambalaj materyalleri ve kontrolsüz depolama koşulları, uçucu yağ kayıpları, fenolik oksidasyonu ve mikrobiyal riskleri artırmaktadır. Raf ömrü boyunca düzenli kalite kontrol yapılmadığında, ürün güvenliği tehlikeye girmektedir.

Genel olarak değerlendirildiğinde, etken madde kayıpları çoğunlukla **önlenebilir riskler** olup; uygun kalite yönetim sistemleri ve bilimsel yaklaşımlarla minimum düzeye indirilebilmektedir.

9.3 Öneriler

1. **Standardizasyon:** Her bitki türü için **fenolojik dönem, kurutma sıcaklığı, ekstraksiyon parametreleri ve raf ömrü kriterleri** ayrı ayrı belirlenmeli ve ulusal/uluslararası farmakopelerde yer almalıdır.
2. **GACP ve GMP Entegrasyonu:** İyi Tarım ve Toplama Uygulamaları (GACP) ile başlayan süreç, İyi Üretim Uygulamaları (GMP) ile desteklenmeli; tüm zincir boyunca izlenebilirlik sağlanmalıdır.
3. **Modern Teknolojilerin Kullanımı:** Süperkritik CO_2 ekstraksiyonu, ultrasonik/mikrodalga destekli kurutma ve ekstraksiyon gibi yöntemler yaygınlaştırılmalıdır. Üniversite–sanayi iş birlikleri ile küçük ölçekli üreticilerin bu teknolojilere erişimi kolaylaştırılmalıdır.
4. **Ambalajlama ve Depolama:** İnert gaz atmosferinde, ışık geçirmez ve oksijen bariyerli ambalajlar kullanılmalı; depolama alanlarında **15–25 °C sıcaklık** ve **%40–50 bağıl nem** sağlanmalıdır.
5. **Kalite Kontrol:** HPLC, GC-MS, LC-MS/MS gibi ileri analitik yöntemlerle her lotun etken madde profili analiz edilmeli; mikrobiyal ve toksikolojik testler düzenli yapılmalıdır.
6. **Sürdürülebilirlik:** Drog hazırlama süreçlerinde enerji verimliliği yüksek, çevre dostu teknolojiler kullanılmalı; atık yönetimi GACP/GMP kapsamında planlanmalıdır.
7. **Eğitim ve Kapasite Geliştirme:** Üreticiler, toplama ekipleri ve laboratuvar çalışanları düzenli olarak **iyi uygulamalar ve kalite yönetimi** konusunda eğitilmelidir.

Etken madde kayıplarının önlenmesi, yalnızca farmasötik kaliteyi değil; aynı zamanda **halk sağlığını, ekonomik sürdürülebilirliği ve uluslararası rekabet gücünü** doğrudan etkilemektedir. Bu nedenle tıbbi bitkilerde drog hazırlama süreci, **multidisipliner bir yaklaşım** (farmakognozi, gıda bilimi, biyoteknoloji, mühendislik, kalite yönetimi) ile yürütülmelidir.

Tablo 5. Drog Hazırlama Sürecinde Etken Madde Kayıpları ve Önleme Stratejileri

Aşama	Risk Faktörü	Etken Madde Kaybı / Değişimi	Önleme Stratejisi
Hasat	Yanlış fenolojik dönem, gün içi zamanlama, mekanik zedelenme	Uçucu yağlarda kayıp, fenoliklerde oksidasyon	Fenolojik takvim takibi, sabah/öğlen optimum hasat, paslanmaz ekipman kullanımı
Taşıma	Gecikmiş işlem, yüksek sıcaklık/nem, plastik torbalar	Uçucu bileşiklerde buharlaşma, mikrobiyal kontaminasyon	Hızlı taşıma, keten/jüt torba, serin ve kuru koşullar
Kurutma	Yüksek sıcaklık (>60 °C), yavaş kurutma, yüksek aw	Vitamin C kaybı, fenolik oksidasyonu, uçucu yağ uçuşması	35–50 °C kontrollü kurutma, hava sirkülasyonu, aw ≤ 0.6 hedefi
Öğütme & Parçalama	Çok ince partikül, yüksek devirde ısınma, metal teması	Oksidasyon artışı, fenoliklerde kompleksleşme	Orta partikül boyutu (0.5–1 mm), inert/paslanmaz çelik değirmen, soğutmalı öğütücüler
Ekstraksiyon	Uzun süreli yüksek ısı, yanlış çözücü seçimi	Termolabil bileşiklerde kayıp, izomerizasyon	Ultrasonik/mikrodalga destekli ekstraksiyon, uygun çözücü (su-etanol) kullanımı
Ambalajlama	Işık ve oksijen maruziyeti, uygunsuz plastik materyal	Uçucu yağ oksidasyonu, renk değişimi, raf ömrü kısalması	Koyu cam/metal folyo, inert atmosfer (N_2/Ar), vakum paketleme
Depolama	Yüksek sıcaklık, nem dalgalanması, uzun süre	Linalool, timol gibi uçucu yağlarda %20'ye varan kayıp	15–25 °C sabit sıcaklık, %40–50 bağıl nem, düzenli kalite analizi

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TIBBİ BİTKİLERDE DROG HAZIRLAMA SÜRECİNDE KALİTE KONTROL PARAMETRELERİ VE STANDARTLAR

MUHAMMET ALİ GÜNDEŞLİ

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ÖZET

Tıbbi bitkilerden elde edilen drogların kalite kontrolü, etkinlik, güvenlik ve standardizasyon açısından kritik öneme sahiptir. Drog hazırlama sürecinde; bitkinin doğru tür ve kısmının kullanımı, hasat zamanı, kurutma koşulları, öğütme derecesi, ambalajlama ve depolama gibi aşamalar kaliteyi doğrudan etkiler. Kalite kontrol parametreleri; **makroskopik ve mikroskopik incelemeler, nem tayini, kül analizleri, etken madde miktar tayini, mikrobiyolojik limit testleri, özgül safsızlıkların belirlenmesi ve organoleptik özelliklerin değerlendirilmesi** gibi yöntemleri içerir. Bu analizler, Avrupa Farmakopesi (Ph. Eur.), Dünya Sağlık Örgütü (WHO) ve ESCOP gibi uluslararası standartlara göre yürütülmelidir. Standardizasyon, her drog partisinde biyoaktif bileşiklerin miktar ve kalitesinin güvence altına alınmasını sağlar. Böylece, tıbbi bitkisel ürünlerin terapötik etkinliği korunur, tüketici güvenliği sağlanır ve ulusal–uluslararası pazarda kabul edilebilirliği artar.

Anahtar Kelimeler: Tıbbi bitkiler · Drog hazırlama · Kalite kontrol · Standardizasyon · Farmakopeler

QUALITY CONTROL PARAMETERS AND STANDARDS IN THE DRUG PREPARATION PROCESS OF MEDICINAL PLANTS

ABSTRACT

The quality control of herbal drugs derived from medicinal plants is of critical importance in terms of efficacy, safety, and standardization. In the drug preparation process, factors such as the correct species and plant part, harvest time, drying conditions, grinding degree, packaging, and storage directly affect quality. Quality control parameters include macroscopic and microscopic examinations, moisture determination, ash analysis, active ingredient quantification, microbiological limit tests, identification of specific impurities, and evaluation of organoleptic properties. These analyses should be conducted according to international standards such as the European Pharmacopoeia (Ph. Eur.), the World Health Organization (WHO), and ESCOP. Standardization ensures the quantity and quality of bioactive compounds in every batch of herbal drugs. Thus, the therapeutic efficacy of herbal medicinal products is preserved, consumer safety is ensured, and their acceptability in national and international markets is enhanced.

Keywords: Medicinal plants • Herbal drug preparation • Quality control • Standardization • Pharmacopoeias

1. GİRİŞ

Tıbbi ve aromatik bitkiler, insanlık tarihinin en eski tedavi araçlarından biri olarak günümüzde de büyük önemini korumaktadır. Dünya Sağlık Örgütü'ne (WHO) göre, dünya nüfusunun yaklaşık %80'i temel sağlık ihtiyaçlarını karşılamak için hâlen bitkisel kökenli tedavilere başvurmaktadır (WHO, 2023). Bu durum, yalnızca geleneksel tıbbın değil, modern farmasötik ve fitoterapötik ürünlerin de bitkisel drog ve ekstreler üzerine inşa edildiğini göstermektedir. Dünya genelinde tıbbi bitkilerin yıllık ticaret hacminin 120 milyar ABD dolarını aştığı, 2050 yılına kadar bu pazarın 5 kat büyümesinin beklendiği bildirilmektedir (Ekor, 2014; Heinrich et al., 2022). Bu artış, tıbbi bitkilerin kalitesine, güvenilirliğine ve standardizasyonuna duyulan ihtiyacı her zamankinden daha önemli hale getirmiştir.

Bitkisel drogların kalitesi, doğrudan etken madde içeriği, saflık, stabilite ve güvenlik parametrelerine bağlıdır. Drog hazırlama sürecinde, hasattan depolamaya kadar olan her aşamada etken madde miktarında değişim, bozulma veya kontaminasyon meydana gelebilir. Bu nedenle kalite kontrol parametrelerinin sistematik bir şekilde uygulanması, ürünün hem farmakolojik etkinliği hem de halk sağlığı açısından güvenliği için zorunludur. Kalite kontrol; bitkinin doğru tür olduğunun teyidinden başlayarak, mikrobiyal ve kimyasal saflık testleri, nem ve kül tayini, organoleptik analizler, etken madde miktar tayini ve raf ömrü değerlendirmelerine kadar uzanan çok yönlü bir süreçtir (WHO, 2023; USP <561>, 2023).

Ulusal ve uluslararası farmakopeler, bu süreci standartlaştırmak için farklı yöntemler geliştirmiştir. Avrupa Farmakopesi (Ph. Eur.), Amerikan Farmakopesi (USP) ve Türk Farmakopesi gibi otoriteler, tıbbi bitkiler için monografiler yayımlamakta; her monografide drogun tanımı, tanımlama kriterleri, saflık testleri ve etkin madde miktar tayini için yöntemler yer almaktadır (Ph. Eur., 2022; Türk Farmakopesi, 2017). Bu monograflar sayesinde farklı coğrafyalarda üretilen ve pazarlanan tıbbi bitkilerde kalite güvence sistemi sağlanabilmektedir. Ancak özellikle gelişmekte olan ülkelerde, sahte veya düşük kaliteli ürünlerin piyasada bulunması hâlâ önemli bir sorundur (Booker et al., 2012).

Kalite kontrol parametrelerinin uygulanmaması, yalnızca etkinliğin azalmasına değil, aynı zamanda ciddi sağlık risklerine de yol açabilir. Örneğin, yüksek nem içeriği nedeniyle aflatoksin kontaminasyonu oluşan tıbbi bitkiler, karaciğer kanseri dahil birçok sağlık problemine zemin hazırlayabilmektedir (Bhat et al., 2010). Benzer şekilde, ağır metal içeren topraklarda yetiştirilen droglar kadmiyum, kurşun ve arsenik kontaminasyonuna maruz kalabilir ve bu maddeler uluslararası limitlerin üzerinde olduğunda halk sağlığı açısından tehdit oluşturur (WHO, 2007). Dolayısıyla kalite kontrol, yalnızca etkinliği artırmak için değil, güvenliği garanti altına almak için de kritik önemdedir.

Son yıllarda tıbbi bitkilerde kalite kontrol, klasik yöntemlerden modern analitik tekniklere doğru önemli bir dönüşüm yaşamaktadır. Nem ve kül tayini gibi basit yöntemler hâlâ önemini korurken; HPLC, GC-MS, LC-MS/MS gibi kromatografik yöntemler, DNA barkodlama ve metabolomik yaklaşımlar kalite standardizasyonunda giderek daha fazla kullanılmaktadır (Parven et al., 2016). Bu gelişmeler, hem sahte ürünlerin tespitini kolaylaştırmakta hem de farmakolojik etkinliği doğrudan belirleyen biyolojik aktif bileşiklerin miktarlarının hassas şekilde ölçülmesine olanak tanımaktadır.

Türkiye açısından bakıldığında, ülkemiz yaklaşık 12.000 bitki taksonuyla dünyanın en zengin floralarından birine sahiptir. Bunun yaklaşık 4.000'i endemiktir ve 500'den fazlası tıbbi ve aromatik bitki olarak kullanılmaktadır (Baytop, 1999; Başer, 2020). Bu zenginlik, Türkiye'yi hem yerel kullanım hem de ihracat açısından stratejik bir konuma getirmektedir. Ancak uluslararası ticarette rekabet gücünün artırılması için, Türk Farmakopesi'nin Avrupa

Farmakopesi ve USP ile uyumlu şekilde güncellenmesi ve kalite kontrol altyapısının güçlendirilmesi gerekmektedir.

Sonuç olarak, tıbbi bitkilerde drog hazırlama sürecinde kalite kontrol parametreleri, hem **etkinlik hem de güvenlik** açısından temel bir zorunluluktur. Farmakopelerde belirtilen standartların yanı sıra modern teknolojilerin entegrasyonu, gelecekte bitkisel drogların daha güvenilir, etkili ve sürdürülebilir bir şekilde kullanılmasına olanak sağlayacaktır.

2. KLASİK KALİTE KONTROL PARAMETRELERİ

Tıbbi bitkilerde drog hazırlama sürecinde kalite kontrolün ilk basamağını klasik farmakopelerce tanımlanan parametreler oluşturur. Bu parametreler, bitkinin fiziksel, kimyasal ve biyolojik özelliklerini değerlendirerek ürünün temel güvenlik ve kalite kriterlerini ortaya koyar. Dünya Sağlık Örgütü (WHO), Avrupa Farmakopesi (Ph. Eur.), Amerikan Farmakopesi (USP) ve Türk Farmakopesi, bu parametreler için belirli standartlar getirmiştir. Aşağıda en yaygın kullanılan klasik kalite kontrol yöntemleri ayrıntılı olarak açıklanmaktadır.

2.1 Nem Tayini

Bitkisel drogların içerdiği **nem oranı**, mikrobiyal gelişim ve kimyasal stabilite üzerinde doğrudan etkiye sahiptir. Yüksek nem, enzimatik reaksiyonları hızlandırarak fenolik bileşiklerde oksidasyona, alkaloidlerde parçalanmaya ve uçucu yağlarda kayıplara yol açar (WHO, 2023). Ayrıca nemli droglar küf ve maya gelişimine uygun ortam oluşturur, bu da aflatoksin gibi mikotoksinlerin oluşmasına neden olabilir (Bhat et al., 2010).

- **Yöntem:** Gravimetrik yöntem en yaygın kullanılan tekniktir. Drog, 105 °C'de sabit ağırlığa ulaşana kadar kurutulur ve kütle kaybı nem miktarı olarak hesaplanır.
- **Farmakope limitleri:** Çoğu bitkisel drogda nem oranı %8–12'nin altında olmalıdır (Ph. Eur., 2022). Örneğin papatya çiçekleri için maksimum %10 nem sınırı belirlenmiştir.
- **Örnek:** *Matricaria chamomilla* (papatya)'da yüksek nemli numunelerde apigenin glikozitleri %20'ye varan oranda parçalanmıştır (Srivastava et al., 2010).

2.2 Kül Tayini

Kül tayini, drog içeriğindeki **inorganik bileşenleri** (mineraller, toprak, kum, metal kalıntıları) belirlemek için yapılan temel testtir.

- **Toplam kül:** Organik bileşenlerin yakılmasıyla geriye kalan inorganik madde miktarıdır.
- **Asitte çözünmeyen kül:** Silika gibi çözünmeyen inorganik kalıntıları gösterir, özellikle toprak ve kum kontaminasyonunu ortaya çıkarır.
- **Suda çözünmeyen kül:** Mineral tuzların çözünürlük özelliklerini değerlendirir.

Farmakope örnekleri:

- *Cassia angustifolia* (sinameki) yapraklarında toplam kül %12'yi, asitte çözünmeyen kül ise %2'yi aşmamalıdır (USP <561>, 2023).
- *Glycyrrhiza glabra* (meyan kökü)'nda kül sınır değeri %8 olarak belirlenmiştir (Ph. Eur., 2022).

Bilimsel bulgu: Yüksek kül miktarı, bitkinin kalitesiz işlendiğini veya sahtecilik amaçlı başka materyallerle karıştırıldığını gösterir (Kumari et al., 2016).

2.3 Organoleptik Özellikler

Organoleptik analiz, drogların **görünüm, renk, koku ve tat** özelliklerinin değerlendirilmesidir. Basit fakat etkili bir yöntemdir.

- **Amaç:** Bitkinin tanımlanması, sahtecilik ve karışıklıkların önlenmesi.
- **Örnek:**
  - Papatya çiçekleri sarı beyaz renkte ve karakteristik elma kokusuna sahiptir.
  - Kekik (Thymus vulgaris) yoğun aromatik ve keskin kokusuyla ayırt edilir.
- **Uygulama:** Farmakopelerde genellikle monografilerde "Tanımlama" kısmında organoleptik özellikler ayrıntılı şekilde tarif edilir.

Organoleptik testler, günümüzde ileri analiz yöntemleri ile desteklenmektedir. Ancak özellikle sahte ürünlerin (örneğin *Digitalis* yaprakları yerine başka yaprakların kullanılması) tespitinde hâlâ ilk basamak olarak önemlidir (Evans, 2009).

2.4 Mikrobiyolojik Limitler

Bitkisel droglar, yetiştirme ve işleme sırasında **mikrobiyal kontaminasyona** maruz kalabilir. Bu durum hem ürünün raf ömrünü azaltır hem de halk sağlığı açısından ciddi riskler doğurur.

- **Önemli patojenler:** *Escherichia coli, Salmonella spp., Staphylococcus aureus, Clostridium perfringens*.
- **WHO ve USP limitleri:**
  - Toplam aerobik bakteri sayısı: $\leq 10^5$ CFU/g
  - Maya ve küf sayısı: $\leq 10^4$ CFU/g
  - *E. coli, Salmonella* gibi patojenler: "Yok" olmalıdır.

Örnek çalışma: Hindistan'da yapılan bir araştırmada pazarda satılan *Withania somnifera* (ashwagandha) köklerinde limitlerin üzerinde mikrobiyal yük saptanmış, bu da üretim ve depolama koşullarının iyileştirilmesi gerektiğini ortaya koymuştur (Mukherjee et al., 2018).

2.5 Yabancı Madde Analizi

Tıbbi drogların içerisine **taş, toprak, böcek parçaları veya başka bitki kısımlarının** karışması, kaliteyi düşüren en yaygın sorunlardan biridir.

- **Farmakope sınırları:** Yabancı madde miktarı genellikle %2–5 arasında sınırlandırılmıştır.
- **Örnek:** *Mentha piperita* (nane) yapraklarında %1'den fazla yabancı maddeye izin verilmez (Ph. Eur., 2022).
- **Analiz yöntemi:** Görsel inceleme, mikroskobik analiz ve taramalı görüntüleme sistemleri kullanılmaktadır.

Bu parametre, hem ticari dürüstlük hem de ürün güvenliği açısından kritik önemdedir.

Klasik kalite kontrol yöntemleri, drogların temel güvenlik ve saflık kriterlerini ortaya koymakta halen vazgeçilmezdir. Nem tayini ile mikrobiyal riskler, kül tayini ile mineral kontaminasyon, organoleptik testlerle tür doğrulaması, mikrobiyoloji ve yabancı madde analizleriyle hijyenik kalite değerlendirilebilmektedir. Bu testler düşük maliyetli, kolay uygulanabilir ve farmakopelerce standartlaştırılmıştır. Ancak modern yöntemlerle

desteklenmediğinde, özellikle etken madde miktar tayini ve sahtecilik tespitinde yetersiz kalabilmektedir. Bu nedenle günümüzde klasik ve modern yöntemler bir arada kullanılmaktadır.

3. MODERN KALİTE KONTROL TEKNİKLERİ

Tıbbi bitkilerde drog kalitesinin güvence altına alınmasında klasik yöntemler temel oluşturmakla birlikte, günümüzde **modern analitik teknikler** kalite standardizasyonunun vazgeçilmez unsurları haline gelmiştir. Kromatografik, spektroskopik ve moleküler biyoloji tabanlı bu yöntemler sayesinde, etken maddelerin **doğrulaması, miktar tayini ve sahtelik tespiti** daha yüksek duyarlılıkla yapılabilmektedir.

3.1 Kromatografik Yöntemler

3.1.1 Yüksek Basınçlı Sıvı Kromatografisi (HPLC)

- **Kullanım alanı:** Flavonoidler, alkaloidler, fenolik asitler, saponinler.
- **Avantajı:** Çok düşük miktarlardaki bileşiklerin hassas tayinine olanak sağlar.
- **Örnek:** *Ginkgo biloba* yapraklarında rutin, kersetin ve ginkgoflavon glikozitlerinin kantitatif tayininde rutin olarak kullanılmaktadır (van Beek, 2005).
- **Türkiye uygulaması:** *Silybum marianum* (devedikeni)'nde silimarin bileşenlerinin standardizasyonu için HPLC-UV analizleri kullanılmaktadır (Küpeli Akkol et al., 2021).

3.1.2 Gaz Kromatografisi-Kütle Spektrometrisi (GC-MS)

- **Kullanım alanı:** Uçucu yağ bileşenleri (terpenler, seskiterpenler, fenilpropenler).
- **Avantajı:** Kompleks uçucu yağ karışımlarını hem ayırır hem de molekül yapısını tanımlar.
- **Örnek:** *Thymus vulgaris* (kekik)'te timol ve karvakrol oranları GC-MS ile belirlenmiş, kemotip farklılıkları ortaya konmuştur (Skoula & Harborne, 2002).
- **Türkiye uygulaması:** GAP bölgesinde yetişen kekik örneklerinde GC-MS analizleriyle yüksek timol kemotipi doğrulanmıştır (Başer, 2020).

3.1.3 LC-MS/MS (Sıvı Kromatografisi – Tandem Kütle Spektrometrisi)

- **Kullanım alanı:** Alkaloidlerin, flavonoidlerin ve fenolik asitlerin iz düzeyde analizi.
- **Avantajı:** Hem ayrıştırma hem de yapısal aydınlatma yapabilir.
- **Örnek:** *Hypericum perforatum* (sarı kantaron)'da hiperisin ve hiperforin miktarlarının LC-MS/MS ile kantitatif tayini yapılmıştır (Southwell and Bourke ., 2001).

3.2 Spektroskopik Yöntemler

3.2.1 UV-Vis Spektroskopisi

- Flavonoidler, fenolik asitler ve karotenoidlerin kantitatif analizinde kullanılmaktadır.
- Basit ve hızlıdır, ancak kompleks karışımlarda selektivitesi düşüktür.

3.2.2 FTIR (Fourier Transform Infrared Spektroskopisi)

- Moleküler fonksiyonel grupların analizinde kullanılır.
- **Örnek:** *Curcuma longa* (zerdeçal)'da kurkuminoidlerin doğrulamasında FTIR kullanılmıştır (Syed et al., 2015).

3.2.3 NMR (Nükleer Manyetik Rezonans)

- Bileşiklerin yapısal aydınlatmasında "altın standart" yöntemdir.
- Ancak yüksek maliyetli olması nedeniyle rutin kalite kontrol yerine araştırma ve doğrulama çalışmalarında kullanılmaktadır.

3.3 DNA Barkodlama ve Moleküler Yöntemler

Tıbbi bitkilerde en büyük sorunlardan biri **yanlış tür kullanımı ve sahtelik**tir. Morfolojik benzerlik gösteren türlerin ayırt edilmesi çoğu zaman zor olabilir. DNA barkodlama, bu sorunu çözmek için geliştirilmiş modern bir tekniktir.

- **Prensip:** Evrensel DNA bölgeleri (ör. rbcL, matK, ITS) sekanslanarak tür tayini yapılır.
- **Örnek:** *Echinacea purpurea* ürünlerinde, farklı Asteraceae türleri ile yapılan sahtecilikler DNA barkodlama ile ortaya çıkarılmıştır (Newmaster et al., 2013).
- **Türkiye uygulaması:** Anadolu'da ticareti yapılan *Origanum* türlerinin DNA barkodlama ile doğrulaması yapılmış ve yanlış etiketleme oranının %15 olduğu rapor edilmiştir (Nazar et al., 2022).

3.4 Metabolomik ve Kemometrik Yaklaşımlar

Son yıllarda **metabolomik profilleme**, bitkisel drogların kalitesini belirlemede güçlü bir araç haline gelmiştir.

- **NMR ve LC-MS tabanlı metabolomik:** Bitkinin tüm metabolit profilini ortaya koyar.
- **Kemometrik analizler (PCA, PLS-DA):** Bölgesel veya ekotip kaynaklı farklılıkların belirlenmesinde kullanılır.
- **Örnek:** *Panax ginseng* örneklerinde metabolomik analizler, farklı kökenlerden gelen numuneler arasındaki kalite farklılıklarını göstermiştir (Park et al., 2014).

Modern kalite kontrol yöntemleri, tıbbi bitkilerde **etken madde standardizasyonu, sahte ürünlerin tespiti ve uluslararası ticaret güvenliği** açısından kritik öneme sahiptir. Klasik yöntemler temel kaliteyi sağlarken, modern yöntemler özellikle **biyolojik aktif bileşiklerin miktar tayini ve doğru tür doğrulaması** için gereklidir. Bu nedenle günümüzde hibrit bir yaklaşım, yani klasik ve modern yöntemlerin birlikte uygulanması en ideal strateji olarak kabul edilmektedir.

4. FARMAKOPELERDE KALİTE STANDARTLARI

Tıbbi bitkilerin küresel ölçekte güvenilir biçimde kullanılabilmesi için, kalite kontrolün **uluslararası standartlarla uyumlu** olarak yapılması gerekir. Bu amaçla Dünya Sağlık Örgütü (WHO), Avrupa Farmakopesi (Ph. Eur.), Amerikan Farmakopesi (USP) ve Türk Farmakopesi gibi otoriteler, bitkisel droglar için **monografl**ar yayımlamaktadır. Bu monograflarda; drogun tanımı, organoleptik özellikleri, saflık testleri, etken madde tayin yöntemleri ve kabul edilebilir limitler yer almaktadır.

4.1 Dünya Sağlık Örgütü (WHO) Standartları

WHO, 1990'lardan itibaren tıbbi bitkilere yönelik kalite kontrol kılavuzları yayımlamaktadır. **"Quality Control Methods for Medicinal Plant Materials"** adlı kılavuz, bitkisel drogların kalite güvencesi için dünya genelinde referans alınmaktadır (WHO, 2023).

- **Tanımlama:** Morfolojik, mikroskobik ve organoleptik özelliklerin tanımı.

- **Saflık testleri:** Nem, kül, yabancı madde, pestisit, ağır metal ve mikrobiyolojik kontaminasyon sınırları.
- **Etken madde tayini:** Gerektiğinde kromatografik yöntemlerle (TLC, HPLC) yapılması önerilir.

Örnek: WHO kılavuzunda *Cassia angustifolia* (sinameki) yaprakları için sennosit A ve B'nin HPLC ile tayini önerilmiştir.

4.2 Avrupa Farmakopesi (Ph. Eur.)

Avrupa Birliği ülkelerinde geçerli olan Avrupa Farmakopesi (Ph. Eur.), bitkisel droglar için en geniş kapsamlı standartları sunmaktadır (Ph. Eur., 2022).

- **Monograflar:** Yaklaşık 200 bitkisel drog için yayımlanmıştır.
- **Testler:** Nem, kül, etanol çözünür ekstrakt, uçucu yağ miktarı, etken madde kantitatif tayini.
- **Kabul limitleri:** Türlere göre değişmektedir.
- **Analitik yöntemler:** HPTLC, HPLC, GC-MS sıklıkla kullanılır.

Örnekler:

- *Matricaria recutita* (papatya) için toplam flavonoid miktarı quercetin eşdeğeri cinsinden ≥0.25% olmalıdır.
- *Thymus vulgaris* (kekik) için uçucu yağ miktarı ≥1.2% (ml/100 g) olarak belirtilmiştir.

4.3 Amerikan Farmakopesi (USP)

ABD'de geçerli olan USP <561> "Articles of Botanical Origin", tıbbi bitkilerin kalite kontrolünde kullanılan kapsamlı bir kılavuzdur (USP, 2023).

- **Sağlık riskleri üzerine odaklanır:** Pestisit kalıntıları, ağır metaller ve aflatoksin limitleri ayrıntılıdır.
- **Aflatoksin sınırları:**
  - Aflatoksin B1 ≤ 5 ppb,
  - Toplam aflatoksin ≤ 20 ppb.
- **Ağır metal limitleri:** Kurşun ≤ 10 ppm, kadmiyum ≤ 0.3 ppm, arsenik ≤ 1 ppm.
- **Mikrobiyolojik limitler:** *E. coli* ve *Salmonella* bulunmamalıdır.

Örnek: *Panax ginseng* monografında ginsenositlerin HPLC ile kantitatif tayini zorunlu kılınmıştır.

4.4 Türk Farmakopesi

Türkiye'de ilk kez 2017'de yayımlanan **Türk Farmakopesi**, bitkisel droglar için de monograflar içermektedir.

- **Kapsam:** 100'den fazla bitkisel drog monografı bulunmaktadır.
- **Testler:** Nem, kül, uçucu yağ miktarı, mikrobiyolojik saflık, yabancı madde.
- **Önem:** Türkiye'nin zengin florası dikkate alındığında, ulusal farmakopenin geliştirilmesi ve Ph. Eur. ile uyumlu hale getirilmesi ihracat açısından stratejiktir.

Örnek: *Foeniculum vulgare* (rezene) meyvelerinde uçucu yağ miktarı %3 (v/w) üzerinde olmalıdır.

Farmakope	Öne Çıkan Özellik	Örnek Parametreler
WHO	Küresel rehber, temel kalite testleri	Nem, kül, yabancı madde, TLC/HPLC
Ph. Eur.	AB standardı, detaylı monograflar	Flavonoid ≥0.25%, uçucu yağ ≥1.2%
USP	Güvenlik odaklı, toksik limitler	Pb ≤ 10 ppm, Aflatoksin B1 ≤ 5 ppb
Türk Farmakopesi	Ulusal standart, uyum süreci	Uçucu yağ miktarı, nem, kül, mikrobiyoloji

Farmakopeler, tıbbi bitkilerin **uluslararası ticarette kabul görmesi** ve **halk sağlığının korunması** açısından vazgeçilmezdir. Ancak standartların ülkeler arasında farklılık göstermesi, özellikle ihracatta sorunlar yaratabilmektedir. Bu nedenle:

- Türk Farmakopesi'nin Avrupa Farmakopesi ve USP ile **uyumlu hale getirilmesi**,
- Laboratuvar altyapısının farmakope gerekliliklerini karşılayacak şekilde güçlendirilmesi,
- Üniversite–sanayi iş birliğiyle yeni monografların geliştirilmesi,

öncelikli adımlar arasında olmalıdır.

5. SONUÇ, DEĞERLENDİRME VE ÖNERİLER

5.1 Sonuç

Bu çalışmada tıbbi bitkilerde drog hazırlama sürecinde kullanılan kalite kontrol parametreleri ve ulusal–uluslararası standartlar kapsamlı biçimde incelenmiştir. Bulgular göstermektedir ki, **drog kalitesi ve güvenliği**, yalnızca etken madde miktarına değil, aynı zamanda nem, kül, organoleptik özellikler, mikrobiyolojik güvenlik ve yabancı madde analizleri gibi çok yönlü parametrelerin izlenmesine bağlıdır. Klasik yöntemler temel kalite ve saflık değerlendirmesinde etkili olmakla birlikte, modern analitik yöntemler (HPLC, GC-MS, LC-MS/MS, DNA barkodlama, metabolomik yaklaşımlar) standardizasyonun sağlanmasında ve sahteciliklerin önlenmesinde kritik rol oynamaktadır.

Farmakopeler (WHO, Ph. Eur., USP, Türk Farmakopesi) tıbbi bitkilerin kalite standartlarını belirleyerek küresel ticarette kabul görebilmesi için ortak bir dil oluşturmaktadır. Ancak ülkeler arasındaki farklı limit değerler, özellikle ihracatta kalite sorunlarını gündeme getirmektedir. Türkiye'nin zengin florası, doğru kalite kontrol ve farmakope uyumuyla küresel pazarda önemli bir rekabet avantajı sağlayabilir.

1. **Klasik yöntemler** (nem tayini, kül tayini, mikrobiyolojik analizler) hızlı, ekonomik ve uygulanabilir olması nedeniyle hâlâ önemini korumaktadır. Ancak bu yöntemler, etkin madde standardizasyonunda tek başına yeterli değildir.

2. **Modern yöntemler** (HPLC, GC-MS, DNA barkodlama) ile etken maddelerin doğru ve güvenilir tayini yapılmakta; böylece ürünlerin hem farmakolojik etkinliği hem de ticari güvenilirliği sağlanmaktadır.

3. **Farmakopeler** kalite kontrolün yasal zeminini oluşturmaktadır. Ancak Türk Farmakopesi'nin Avrupa Farmakopesi (Ph. Eur.) ve USP ile daha fazla uyumlaştırılması, ihracatta engellerin azaltılmasını sağlayacaktır.

4. **Türkiye'de laboratuvar altyapısı**, modern analitik teknikleri uygulayabilecek düzeye getirilmelidir. Aksi halde uluslararası pazarlarda ürünlerin kabulü güçleşmektedir.

5. **Sahtecilik ve yanlış tür kullanımı**, tıbbi bitkilerin en büyük sorunlarından biridir. DNA barkodlama ve metabolomik yaklaşımlar bu sorunların çözümünde etkin bir araç olarak öne çıkmaktadır.

Öneriler

a) Akademi İçin

- Üniversitelerde farmakognozi, fitokimya ve farmasötik botanik alanlarında **nitelikli araştırmalar** desteklenmeli.
- Modern analitik tekniklerin kullanıldığı **multidisipliner projeler** artırılmalı.
- Türk Farmakopesi'nin geliştirilmesi için akademisyenlerin aktif katkısı sağlanmalı.

b) Sanayi İçin

- GMP (İyi Üretim Uygulamaları) ve ISO standartlarına uyum zorunlu hale getirilmeli.
- Drog hazırlamada **parti bazlı izlenebilirlik** (traceability) sağlanmalı.
- Modern laboratuvar altyapısına yatırım yapılmalı, rutin kalite kontrol süreçleri yalnızca klasik yöntemlerle sınırlı kalmamalı.

c) Politika Yapıcılar İçin

- Tıbbi bitkilerin ihracatında **uluslararası farmakopelere uyum** zorunlu hale getirilmeli.
- Bitkisel ürünlerde sahtecilik ve kalite kontrol eksikliği ile mücadele için **daha sıkı regülasyonlar** uygulanmalı.
- Türkiye'nin zengin florasını korumak için **sürdürülebilir üretim ve koruma stratejileri** geliştirilmeli.

Sonuç olarak, tıbbi bitkilerde kalite kontrol, yalnızca akademik bir gereklilik değil; aynı zamanda **halk sağlığını koruyan, ekonomik katma değer yaratan ve uluslararası pazarlarda güven sağlayan stratejik bir zorunluluktur**. Türkiye'nin doğal zenginlikleri, farmakopelere uyumlu kalite kontrol sistemleriyle desteklendiğinde, ülkemiz dünya bitkisel ürün ticaretinde öncü ülkelerden biri haline gelebilir.

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POSTBIOTIC ORGANIC ACIDS PRODUCED BY FOOD- AND SEAFOOD-ISOLATED LAB STRAINS: CHEMISTRY, FUNCTIONAL ROLES, AND HEALTH IMPLICATIONS

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ABSTRACT

Postbiotics, which are defined as non-viable microbial cells, cell components or metabolic by-products, are emerging as bioactive compounds with significant applications in food science and health. Postbiotic organic acids are a particularly important class due to their multifunctional properties, including antimicrobial activity, antioxidant potential, modulation of the gut microbiota and support of intestinal health. Lactic acid bacteria (LAB) strains, which are found in various foods such as fermented dairy products, vegetables, cereals and seafood, are the main producers of these metabolites. The main postbiotic organic acids are lactic acid, acetic acid, propionic acid, butyric acid, formic acid, and valeric acid. Each of these acids has a distinct chemical profile and functional role. Lactic acid reduces intestinal pH, thereby inhibiting pathogenic bacteria such as E. coli and Salmonella, while strengthening epithelial barrier function and providing moderate antioxidant activity. Acetic acid modulates the composition of the gut microbiota, promotes the colonisation of probiotics, and exhibits broad-spectrum antimicrobial and antioxidant effects. Propionic acid is a short-chain fatty acid (SCFA) that supplies energy to colonocytes, reduces inflammation, and exhibits potent antimicrobial and antioxidant activity. Butyric acid is a primary energy source for colon epithelial cells. It enhances mucosal barrier integrity, inhibits pathogens including Clostridium difficile, and exhibits strong antioxidant and anti-inflammatory effects. Formic and valeric acids contribute to pH regulation and pathogen inhibition, providing moderate antioxidant protection. A comprehensive overview of the production, chemical characteristics and functional effects of postbiotic organic acids from LAB strains isolated from food and seafood is offered by this study. The interactions of these acids with the host, including the activation and modulation of SCFA receptors and intestinal epithelial cells, highlight their importance in maintaining gut homeostasis and systemic health. Additionally, technological and industrial considerations are discussed, such as the incorporation of these acids into functional foods, their stability during processing and storage, and the associated regulatory challenges. Integrating perspectives from microbiology, food chemistry, and nutritional science, this work emphasises the importance of LAB-derived postbiotic organic acids as multifunctional bioactive compounds that bridge food technology and health promotion. It also explores their potential applications in designing next-generation functional foods and dietary interventions.

Keywords: Postbiotic organic acids; Lactic acid bacteria; Functional foods; Gut health; Antimicrobial activity; Antioxidant properties

1. Introduction

Probiotics and postbiotics have gradually become the focus of scientific and nutritional research [1]. LAB strains from different sources, such as food versus seafood, display distinct metabolite profiles due to environmental adaptation. Seafood-derived LAB are often adapted to saline, protein-rich environments, which may affect their stress tolerance and postbiotic production profiles (Abdul Hakim et al., 2023; Venugopal et al., 2023). Seafood-derived LAB strains exhibit unique metabolic capacities compared to terrestrial sources due to adaptation to marine environments. These postbiotic organic acids interact with host physiology via short-chain fatty acid (SCFA) receptors such as GPR41/43, regulating immune responses, maintaining epithelial barrier integrity, and reducing inflammation (Hu et al., 2025). They also contribute to microbial balance in the gut, creating unfavorable conditions for pathogenic bacteria (Zalán et al., 2010). Functional incorporation of these acids in foods provides both technological benefits and health-promoting effects, though metabolite stability, production conditions, and safety assessments must be considered (Shah et al., 2020; Ajiboye et al., 2021).

This study therefore aims to compare and highlight the organic acid, short-chain fatty acid and vitamin compositions of postbiotics produced by LAB, with a view to selecting the most promising strains for nutritional evaluation and potential industrial application in food systems.

1.2. Postbiotics

Postbiotics, defined as non-viable microbial cells, cell components, or metabolic by-products, are emerging as bioactive compounds with important applications in food science and human health (Aguilar-Toalá et al., 2018; Teame et al., 2020). Postbiotics were described as a mixture of inanimate microbes and/or their elements that provide health benefits to the host directly or indirectly [Aguilar-Toalá et al., 2018; Teame et al.,, 2020]. So, the term 'postbiotic' refers to substances like proteins, B vitamins, peptides, carbs, organic acids, polysaccharides, enzymes, or any other soluble factor (product or metabolic by-product) of microbial metabolisms that are derived after the microorganisms are dead or inanimate [Rad et al., 2020; Rafique et al., 2023]. Furthermore, postbiotics must be derived from well-defined, food-grade microorganisms, which are released following cell lysis during the growth and fermentation of complex microbiological cultures, foods, or the gut environment [Thorakkattu et al., 2022].

Several investigators have proposed multiple terminologies to describe non-viable microbial preparations, including postbiotics and paraprobiotics, using terms such as *non-viable probiotics*, *inactivated probiotics*, *non-biotics*, *ghost probiotics*, and *metabiotics* (Tsilingiri et al., 2012 [24]; Piqué et al., 2019 [28]; Singhal et al., 2018 [29]). Paraprobiotics have been defined similarly to the FAO/WHO definition of probiotics, with minor modifications, as inactivated (non-viable) microbial cells which, when administered in adequate amounts, confer health benefits to the consumer (FAO/WHO, 2001 [30]). To resolve discrepancies in terminology, a recent consensus article by Piqué, Berlanga, and Miñana-Galbis (2019) [31] proposed a clearer classification: (i) postbiotics, defined as non-viable bacterial products or metabolic products from microorganisms that exert biological activity in the host; (ii) paraprobiotics (ghost or inactivated probiotics), defined as non-viable microbial cells—intact or fragmented—or crude cell extracts that provide health benefits when administered orally or topically; and (iii) probioceuticals, referring to specific probiotic-derived bioactive molecules such as reuterin from *Lactobacillus reuteri*. According to more recent interpretations (Zółkiewicz et al., 2020 [32]), paraprobiotics represent dead or inactivated probiotic cells (intact or lysed) or crude cell extracts containing complex cellular components, whereas postbiotics are cell-free supernatants containing metabolic products such as enzymes, secreted proteins, peptides, vitamins, amino acids, short-chain fatty acids, and organic acids (Aguilar-

Toalá et al., 2019 [33]; Wegh et al., 2019 [34]). Adding postbiotics to dairy products can significantly affect their sensory characteristics and is a novel way to enhance their microbial safety due to producing a large number of antioxidant enzymes [Wang et al., 2021]. Nutrients such as vitamins B12 and K, folate, and amino acids, which can be produced by gut bacteria, are examples of postbiotics. Other types include lipopolysaccharides. Enzymes are another type. So are short-chain fatty acids. Bacterial lysates are another type. Cell-free supernants are another type [Ibrahim et al., 2024]. These compounds exhibit anti-inflammatory, antioxidant, and antihypertensive activities, contributing to gut and systemic health (Aguilar-Toalá et al., 2018; Salminen et al., 2021). Due to their chemical stability, postbiotics can be incorporated into functional foods as safe alternatives to live cultures (Rafique et al., 2023).

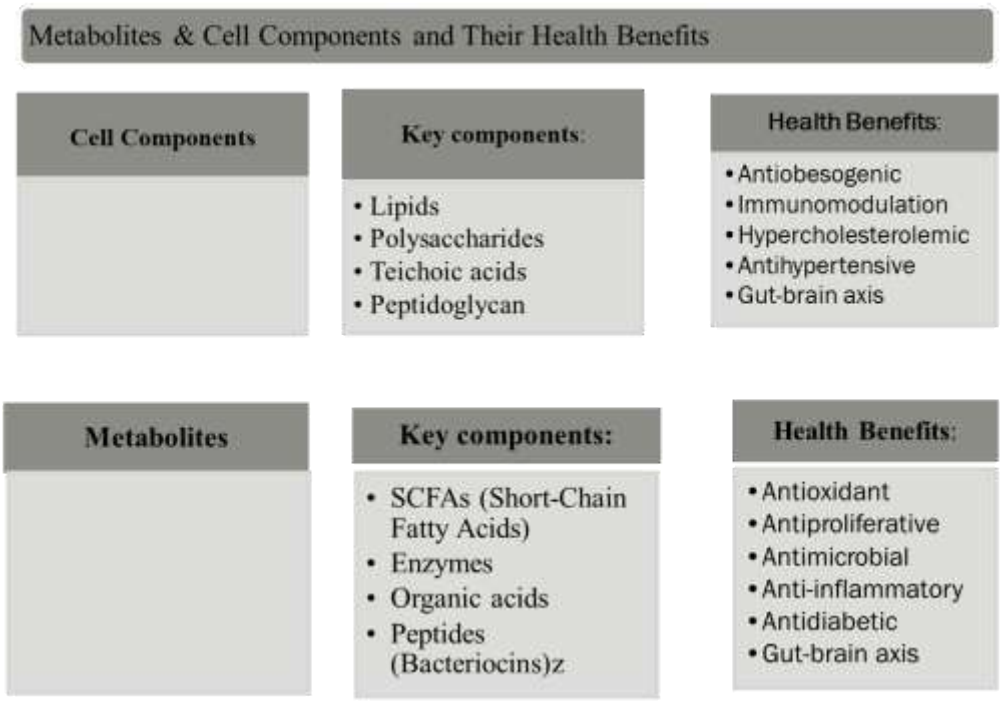

Fig. 1. Benefits of postbiotic such as metabolites and cell component

Postbiotics have several advantages over probiotics, including greater stability, a longer shelf life, increased safety and higher tolerance to environmental stress. Postbiotics have been found to be more resistant to food processing conditions and have been shown to remain active for longer periods, according to Moradi et al. 2019. Noori et al. [2023] emphasised that large quantities of postbiotics are used in the food industry to develop functional foods. Generally speaking, postbiotics exert many of the same beneficial effects as probiotics [Jang et al., 2024]. Research has also demonstrated the effectiveness of postbiotics in preventing paediatric acute gastroenteritis when consumed in fermented cow's milk containing Lacticaseibacillus paracasei (Mishra et al., 2025).

1.2.1 Microbial Metabolites

Microbial metabolites constitute one of the most functionally important categories of postbiotics, produced during the fermentation of dietary substrates by beneficial microorganisms. These metabolites include short-chain fatty acids (SCFAs), tryptophan-derived indoles, bacteriocins, bioactive peptides, amino acids, secreted proteins, and extracellular vesicles, each contributing to host health through distinct biochemical mechanisms (Cummings & Macfarlane, 1991; Shenderov, 2017). SCFAs such as acetate,

propionate, and butyrate are particularly significant due to their roles in regulating immune responses, enhancing epithelial barrier integrity, modulating oxidative stress, and supporting metabolic homeostasis (Canani et al., 2011; Belenguer et al., 2006; Scheppach, 1994). These acids also exert antimicrobial effects by lowering luminal pH and disrupting pathogenic cell membranes (Gonzalez, Lee, Schluter, Ravel & Patterson, 2014). Additional microbial metabolites—including tryptophan catabolites—further influence gut–immune and gut–brain signaling pathways, enhancing mucosal tolerance and reducing inflammation (Thorburn, Macia & Mackay, 2014; Kudryasheva, 2004). Collectively, these postbiotic-derived metabolites form the biochemical foundation of the therapeutic and nutritional benefits attributed to postbiotic interventions, demonstrating improved stability, safety, and functional consistency compared to live probiotic formulations (Cremon et al., 2017; Nataraj, Ali, Behare & Yadav, 2020).

Chain Fatty Acids (SCFAs)

Short-chain fatty acids (SCFAs)—primarily acetate, propionate, and butyrate—are the most abundant microbial fermentation products and represent the core functional group of postbiotic metabolites. Produced through microbial fermentation of dietary fibers that escape digestion, SCFAs exert wide-ranging physiological effects, including energy supply for colonocytes, reinforcement of epithelial barrier integrity, and maintenance of mucosal homeostasis (Cummings & Macfarlane, 1991). SCFAs regulate host immunity and inflammation through G-protein-coupled receptors—particularly GPR41, GPR43, and GPR109A—modulating cytokine production and promoting anti-inflammatory responses such as IL-10 secretion (Thorburn, Macia & Mackay, 2014).

Clinically, butyrate demonstrates strong therapeutic potential; rectal butyrate administration has been shown to improve mucosal healing and reduce symptoms in ulcerative colitis through mechanisms involving histone deacetylase (HDAC) inhibition and suppression of NF-κB signaling (Canani, Costanzo, Leone, Pedata, Meli & Calignano, 2011). SCFAs also contribute to metabolic homeostasis by regulating glucose and lipid pathways, reducing lipogenesis, and enhancing mitochondrial function, collectively lowering the risk of metabolic syndrome (Belenguer, Duncan, Calder, Holtrop, Louis, Lobley & Flint, 2006).

Additionally, organic acids act synergistically with other postbiotic metabolites; for example, SCFAs markedly inhibit enteric pathogens such as *Escherichia coli* and *Clostridium difficile* through pH reduction, membrane disruption, and intracellular acidification (Gonzalez, Lee, Schluter, Ravel & Patterson, 2014). Further microbial products—including tryptophan-derived indoles—contribute to gut–immune and gut–brain signaling networks, supporting immune tolerance and epithelial protection (Shenderov, 2017; Kudryasheva, 2004). Collectively, these mechanisms underline the central role of SCFAs as key mediators of postbiotic biological activity and host metabolic and immune regulation.

Microbial Enzymes

Microbial enzymes are also considered postbiotic components due to their bioactivity and health-promoting effects. These include digestive enzymes that facilitate the breakdown of complex carbohydrates, proteins, and lipids, thereby enhancing nutrient absorption and supporting gastrointestinal function.

Additionally, certain enzymes and enzyme-derived peptides—such as bacteriocins—exhibit potent antimicrobial activity. Bacteriocins inhibit the growth of pathogenic microorganisms, contribute to colonization resistance, and help maintain microbial balance within the gut

ecosystem [7]. Through these mechanisms, microbial enzymes play a significant role in protecting the host against infections and improving overall gut health.

1.2.2. Microbial Cell Components

Microbial cell components such as peptidoglycans, lipoteichoic acids, lipopolysaccharides, exopolysaccharides (EPS), surface proteins, and cell wall fragments represent a major functional category of postbiotics due to their direct interactions with host epithelial and immune cells. These structural molecules can activate pattern-recognition receptors—including TLR2, TLR4, and NOD2—leading to controlled immune modulation, enhanced mucosal protection, and reduced inflammatory signaling (Aguilar-Toalá et al., 2018; Salminen et al., 2021). Exopolysaccharides produced by LAB contribute to intestinal barrier strengthening by promoting tight-junction protein expression and improving epithelial resistance to oxidative and inflammatory stress (Ibrahim et al., 2024). Peptidoglycan fragments and surface-layer proteins also influence dendritic-cell maturation and cytokine production, supporting both innate and adaptive immune functions (Thorakkattu et al., 2022). Collectively, these microbial cell-derived compounds constitute a core component of postbiotic functionality, contributing to gut homeostasis, epithelial integrity, and host immune regulation.

1.3. Postbiotic Metabolites: Organic acids

Organic acids are among the most biologically active postbiotic metabolites, forming a key link between microbial fermentation, gut physiology and host health. Postbiotics include a variety of microbial cellular components, such as peptidoglycans, lipoteichoic acids and exopolysaccharides (EPS), but their core function is primarily driven by organic acids produced during the microbial breakdown of dietary substrates. These acids modulate gut pH, inhibit pathogens, and shape immune tolerance, epithelial integrity, and metabolic signalling (Aguilar-Toalá et al., 2018; Salminen et al., 2021).

Dietary carbohydrates that escape human enzymatic digestion, particularly indigestible fibres, are essential for synthesising postbiotic organic acids. These fermentable substrates are selectively metabolised by gut microorganisms into short-chain fatty acids (SCFAs), primarily acetate, propionate and butyrate (Cummings & Macfarlane, 1991). Their formation depends on specific microbial pathways: Lactobacilli convert carbohydrates to pyruvate via glycolysis, and then to lactate and acetate. Heterofermentative lactic acid bacteria (LAB) utilise the phosphoketolase pathway (Table 1), while bifidobacteria generate acetate, lactate, and formate depending on substrate availability (Rivière, Selak, Lantin, Leroy & De Vuyst, 2016).

Table 1. Organic acid chemical Formula, basic chemical structure, Mechanism of Action

Organic Acid	Chemical Formula (Kapalı Formül)	Basic Chemical Structure (Özet)	Mechanism of Action
Lactic acid	$C_3H_6O_3$	α-hydroxy acid; CH_3–CH(OH)–COOH	Lowers pH, disrupts pathogen membranes via proton influx; precursor for butyrate production; modulates immune pathways via GPR81
Acetic acid	$C_2H_4O_2$	Simple monocarboxylic acid; CH_3–COOH	Rapid systemic absorption; activates GPR43/41; reduces intracellular pH of pathogens
Propionic acid	$C_3H_6O_2$	CH_3–CH_2–COOH	Inhibits hepatic HMG-CoA reductase; modulates gluconeogenesis; acidifies gut lumen
Butyric acid	$C_4H_8O_2$	CH_3–CH_2–CH_2–COOH	Primary colonocyte energy source (via MCT1 transport); potent HDAC inhibitor; improves barrier integrity
Formic acid	CH_2O_2	H–COOH	Strong acidifier; disrupts microbial electron transport; inhibits bacterial metabolism
Valeric acid	$C_5H_{10}O_2$	CH_3–$(CH_2)_3$–COOH	GPCR activation (GPR41 affinity); modulates neuronal and immune signaling
Caproic acid (Hexanoic acid)	$C_6H_{12}O_2$	CH_3–$(CH_2)_4$–COOH	Disrupts pathogen lipid bilayers by chain penetration
Pyruvic acid	$C_3H_4O_3$	CH_3–CO–COOH	Central intermediate linking glycolysis to SCFA production; antioxidant electron sink
Succinic acid	$C_4H_6O_4$	HOOC–CH_2–CH_2–COOH	Activates SUCNR1 receptor; modulates macrophage metabolism
Malic acid	$C_4H_6O_5$	HOOC–CH_2–CHOH–COOH	TCA cycle intermediate; contributes to redox balance
Citric acid	$C_6H_8O_7$	HOOC–CH_2–C(OH)(COOH)–CH_2–COOH	Chelates metal ions; lowers pH; enhances microbial inhibition
Phenyllactic acid	$C_9H_{10}O_3$	Aromatic α-hydroxy acid	Disrupts pathogen cell membranes; interferes with quorum sensing
Indole-3-lactic acid	$C_{11}H_{11}NO_3$	Indole-derived hydroxy acid	Aryl hydrocarbon receptor (AhR) agonist

During these processes, species such as *Lactobacillus* and *Bifidobacterium* metabolise prebiotic substrates and release extracellular acids, while intracellular fractions can be obtained by deliberately disrupting the cells. Methods of extraction and purification—including enzymatic or thermal treatment, membrane filtration, centrifugation, sonication, high-pressure processing, dialysis, solvent extraction and lyophilisation—enable the precise recovery of these metabolites for therapeutic and technological applications (Nataraj et al., 2020).

The generation of postbiotic organic acids depends on controlled microbial fermentation. Seafood-associated LAB species, such as Lactobacillus plantarum and L. sakei, are emerging as promising sources of postbiotic organic acids due to their ability to adapt to saline, protein-rich marine environments. These strains demonstrate high stress tolerance and distinctive metabolic capabilities, producing stable and diverse organic acid profiles with potential applications in food biotechnology and the development of functional ingredients (Venugopal et al., 2023; Abdul Hakim et al., 2023). Together, the synthesis, extraction and biological activity of organic acids are at the heart of postbiotic functionality. Their capacity to integrate microbial metabolism with host immune, epithelial and metabolic responses highlights their significance as fundamental mediators of gut health.

Lactic acid represents the principal organic acid produced by LAB and plays a central role in antimicrobial defense by lowering environmental pH and enhancing host immune responses (Begunova, 2022). Lactic acid and lactate also serve as metabolic intermediates for the production of **butyrate**, a key short-chain fatty acid essential for colonocyte energy metabolism and the maintenance of intestinal epithelial integrity (Belenguer et al., 2006; Scheppach, 1994).

Acetic acid, another dominant metabolite, is rapidly absorbed into systemic circulation and participates in metabolic and immune signaling; experimental models demonstrate that elevated acetate levels can enhance resistance to infection (Thorburn et al., 2014). **Propionic acid** exhibits anti-inflammatory activity and has been shown to inhibit hepatic cholesterol synthesis through its effects on metabolic pathways (Bush & Milligan, 1971). In addition to these major SCFAs, LAB produce **formic and valeric acids**, which contribute to maintaining gut ecological stability by acidifying the intestinal environment, thereby reducing pathogen viability (Zalán et al., 2010).

Propionic acid is comprised of three carbonic acids and occurs naturally in milk and other dairy products. It is produced in the process of natural fermentation by *Propionibacterium*. It is also added as a food preservative. It has antibacterial and antifungal properties.The biological activity of these organic acids begins immediately upon entering the gastrointestinal tract, as postbiotics reach the colon largely unchanged, circumventing the colonization requirements associated with live probiotic cells (Ardatskaya et al., 2020). Their combined antimicrobial, antioxidant, immunomodulatory, and metabolic roles support gut homeostasis and systemic health (Shenderov, 2017; Kudryasheva, 2004).

Mechanisms of Action of SCFA-Driven Organic Acids

Postbiotic metabolites, those produced by lactic acid bacteria (LAB) are the most widely studied and functionally important. Lactic, acetic, propionic, butyric, formic and valeric acids contribute to microbial competitiveness, food preservation and host physiological regulation by modulating pH, exhibiting antimicrobial activity and producing redox effects and SCFA-mediated metabolic signalling (Prajapati et al., 2023; Ranjha et al., 2021; Amobonye et al., 2025).

Each SCFA follows a distinct metabolic fate and engages specific host receptors. Acetate diffuses systemically and activates GPR41 and GPR43, modulating metabolic and immune pathways (Thorburn, Macia & Mackay, 2014). Propionate serves as a substrate for hepatic gluconeogenesis and suppresses cholesterol synthesis via inhibition of HMG-CoA reductase (Bush & Milligan, 1971). Butyrate, transported into colonocytes through the monocarboxylate transporter MCT1, is their primary energy source and acts as a potent histone deacetylase inhibitor (HDACi), mediating epigenetic regulation of gene expression, strengthening epithelial tight junctions, suppressing NF-κB signaling, and inducing apoptosis in dysplastic cells (Prajapati, et al. 2023).

These chemical mechanisms form the basis of the well-documented health effects of SCFAs. By supporting colonocyte metabolism and enhancing tight junction integrity, organic acids reinforce the intestinal barrier and increase transepithelial electrical resistance (TEER), preventing microbial translocation (Cremon et al., 2017; multiple TEER studies 2010–2018). SCFA–receptor interactions promote IL-10 production, enhance mucosal tolerance, and reduce pro-inflammatory cytokines, contributing to clinical improvement in conditions such as IBD, IBS, and metabolic syndrome (Shenderov, 2017; Kudryasheva, 2004). Additionally, synergistic mixtures of acetate, propionate, and butyrate inhibit enteric pathogens including *Clostridium difficile* and *Escherichia coli*, through mechanisms involving pH stress, membrane disruption,

and intracellular acidification (Gonzalez, et al., 2014). Collectively, these biochemical pathways confirm that LAB-derived organic acids function not only as key postbiotic metabolites but also as central regulators of gut homeostasis, immune modulation, and host metabolic health (Belenguer et al., 2006).

Marine-Isolated Probiotics and Their Organic Acid Profiles

Marine-isolated probiotics are beneficial microorganisms derived from seawater or marine organisms such as fish, shellfish, and shrimp. Adaptation to the marine ecosystem provides these strains with advantages including salt tolerance, temperature resilience, and strong competitive fitness in saline environments. In aquaculture, they offer significant potential for enhancing animal health, improving immune responses, and increasing feed efficiency (Fernández-Alarcón et al., 2021; Martínez-Cámara et al., 2023). Beyond aquaculture, marine-origin probiotics can also be incorporated into the food industry as functional food components, expanding the diversity of beneficial microbes beyond traditional dairy-associated strains.

Seafood-derived probiotics and their metabolic products—particularly postbiotic organic acids such as lactic, acetic, propionic, butyric, formic, valeric, succinic, and citric acids—play central roles in microbial ecology and host physiology. These acids reduce environmental pH, disrupt pathogenic membranes, regulate oxidative stress, and support gut homeostasis through SCFA-mediated signaling pathways (Cummings & Macfarlane, 1991; Gonzalez et al., 2014). Once produced, LAB-derived organic acids reach the colon largely intact, bypassing the need for microbial colonization and providing immediate biological activity (Shenderov, 2017; Kudryasheva, 2004). Their systemic effects involve GPCR-mediated immunometabolic signaling, while butyrate further exerts epigenetic effects via histone deacetylase inhibition, contributing to epithelial barrier strengthening, anti-inflammatory activity, and regulation of cellular homeostasis (Thorburn, Macia & Mackay, 2014)

Marine-associated LAB—including *Lactobacillus plantarum* and *L. sakei*—have evolved unique metabolic traits driven by exposure to saline and protein-rich environments. As a result, they generate diverse and stable profiles of organic acids, offering high functional potential for food technology and next-generation nutraceuticals (Venugopal et al., 2023; Abdul Hakim et al., 2023). Additional marine isolates, such as bacteriocin-producing LAB from gilthead seabream, antioxidant- and enzyme-producing *Bacillus* strains, and marine yeasts like *Yarrowia lipolytica*, display strong antimicrobial, immunomodulatory, and biopreservative properties relevant to both aquaculture and human food systems (Fernández-Alarcón et al., 2021).

The functional benefits associated with marine-derived probiotics include enhanced host immunity, inhibition of pathogenic microorganisms, improved growth performance in aquaculture species, and suitability for incorporation into functional-food formulations. However, their broader application requires rigorous safety assessment—including evaluation of virulence and antibiotic-resistance genes—as well as establishment of regulatory guidelines and scalable industrial production systems (Mayer & Santos, 2011; Kumar et al., 2025). Postbiotics derived from these strains, including SCFAs, cell wall fragments, enzymes, exopolysaccharides, and cell-free supernatants, offer chemically stable and well-defined structures with demonstrated bioactivity, presenting a controlled and safer alternative to live probiotics in therapeutic and industrial contexts (Cummings & Macfarlane, 1991; Cremon et al., 2017).

Their incorporation into functional foods guarantees consistent bioactivity, reliable fermentation results, prolonged shelf life, and the maintenance of biochemical functionality in

products aimed at enhancing cognitive or metabolic function (Scott, et al., 2022). Collectively, seafood-derived probiotics and their postbiotic organic acids function as multifunctional bioactive agents that integrate microbial metabolism, food biotechnology, and host health, demonstrating strong potential for application in next-generation functional foods and targeted nutritional interventions (Belenguer et al., 2006; Thorburn, Macia & Mackay, 2014).

Health Effects of Postbiotic Organic Acids

Their structural stability and resistance to gastrointestinal degradation further enhance their The human gut microbiota is now recognized as a central regulator of systemic and mental health through the microbiota–gut–brain axis (MGBA), a bidirectional communication network linking intestinal microorganisms with neural, immune, and endocrine pathways (Marano et al., 2023). Advances in microbial therapeutics have highlighted probiotics, prebiotics, postbiotics, and synbiotics as next-generation functional biotics with neuroactive potential (Schneider et al., 2024). Probiotic microorganisms—particularly *Lactobacillus* and *Bifidobacterium* species—not only support intestinal homeostasis but also synthesize key biogenic amines such as serotonin, dopamine, γ-aminobutyric acid (GABA), and tryptamine, which function as microbial neurotransmitters influencing stress responses, cognition, and emotional regulation (Ranjha et al., 2021; Ramesh et al., 2024; Bleibel et al., 2023). These neuroactive metabolites form the biochemical foundation of psychobiotic action, demonstrating how gut microorganisms modulate central nervous system function and contribute to improved mental well-being (Cryan et al., 2021).Postbiotic derivatives—consisting of inactivated microbial biomass and secreted metabolites—serve as reproducible metabolic platforms with enhanced safety and stability (Islam et al., 2024; Zhu et al., 2025). Thermal, enzymatic, or mechanical inactivation preserves key metabolites such as peptides, short-chain fatty acids, and amino acid derivatives, which maintain bioactivity, modulate fermentation kinetics, and influence co-cultured strains (Amobonye et al., 2025).

Once synthesised, organic acids exert an immediate biochemical effect within the intestinal lumen. By lowering the pH level, they disrupt the membrane integrity of pathogenic bacteria through proton influx and the collapse of the proton motive force — an established antimicrobial mechanism (Gonzalez, Lee, Schluter, Ravel & Patterson, 2014). In addition to these effects in the intestinal lumen, SCFAs act as signalling molecules that regulate epithelial energy metabolism, mucosal repair, tight-junction assembly, oxidative balance and immune pathways. This contributes significantly to maintaining gut homeostasis (Canani et al., 2011; Scheppach, 1994).

This shift represents a paradigm change in microbial biotechnology: survival-based probiotic models are increasingly complemented or replaced by metabolite-driven psychobiotic systems. Microbial metabolites now form the fundamental building blocks for functional innovation, bridging food science, metabolic engineering, and microbial ecology to create reproducible, scalable, and neuroactive bioproducts suitable for advanced nutritional and biotechnological applications (Kyei-Baffour et al., 2025; Rocchetti et al., 2025).

Table 2. Microbial Organic Acids: Functions and Health Effects

Acid	Category / Source	Function / Purpose	Effects on Gut Health	Antimicrobial Effect	Antioxidant Effect
Lactic Acid	Lactic acid bacteria (LAB)	pH regulator; probiotic-derived metabolite	Lowers gut pH; inhibits pathogen growth; strengthens epithelial barrier	Inhibits Gram-negative and Gram-positive pathogens (e.g., *E. coli*, *Salmonella*)	Moderate antioxidant activity
Acetic Acid	LAB; fermentation end product	Antimicrobial; metabolic regulator	Modulates gut microbiota; supports probiotic colonization	Broad-spectrum antimicrobial activity (*Salmonella*, *Listeria*)	Mild antioxidant; reduces lipid peroxidation
Propionic Acid	*Propionibacterium* species	SCFA; energy and metabolic regulator	Provides energy to colon cells; reduces inflammation	Inhibits several intestinal pathogens	Strong antioxidant activity
Butyric Acid	*Clostridia* and some LAB	SCFA; anti-inflammatory; energy source	Primary fuel for colonocytes; strengthens mucosal barrier; decreases inflammation	Inhibits pathogens, especially *Clostridium difficile*	Strong antioxidant; protects epithelial cells
Formic Acid	LAB and some *Bacillus* strains	Acidifier; preservative	Stabilizes gut microbiota; suppresses pathogen growth	Effective antimicrobial, especially against enteric pathogens	Mild antioxidant effect
Valeric Acid	SCFA; various fermentative bacteria	Anti-inflammatory; metabolic support	Enhances gut barrier; reduces inflammatory responses	Helps inhibit pathogen colonization	Moderate antioxidant activity

Conclusion

In summary, LAB-derived and marine-derived postbiotic organic acids are multifunctional microbial metabolites that integrate antimicrobial defense, immune regulation, epithelial barrier enhancement, and metabolic signaling into a single bioactive framework. Their chemical stability, defined molecular structures, and independence from microbial viability make them advantageous alternatives to conventional probiotics, particularly in functional foods, aquaculture, and therapeutic nutrition. The diverse biochemical mechanisms of acetate, propionate, butyrate, and related organic acids highlight their central role in maintaining gut homeostasis and systemic health. Collectively, these compounds exemplify the next generation of postbiotic interventions, offering reliable, safe, and efficacious strategies for targeted nutritional and biomedical applications.

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ANTIBIOTIC RESISTANCE IN SEAFOOD-DERIVED PROBIOTIC STRAINS: MECHANISMS, PREVALENCE, AND SAFETY IMPLICATIONS

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ABSTRACT

Probiotic strains derived from seafood, particularly lactic acid bacteria (LAB), are widely used in aquaculture and functional foods due to their health-promoting properties, which include inhibiting pathogens, modulating gut microbiota and enhancing host immunity. These microorganisms improve the functional quality of seafood-based products and support the health of aquatic animals and human consumers. However, some probiotic strains may harbour antibiotic resistance (AR) genes, which could be transferred to other microorganisms through horizontal gene transfer, representing a potential biosafety concern. Antibiotic resistance in probiotics can be intrinsic or acquired through mobile genetic elements such as plasmids, transposons, and integrons. Mechanisms include the enzymatic inactivation of antibiotics, efflux pump activity and the modification of antibiotic targets. The variation in AR traits among LAB species and strains highlights the importance of carefully selecting and characterising probiotic candidates. To ensure the safe use of seafood-derived probiotics, systematic strain screening, genomic characterisation and adherence to regulatory guidelines are required. Selecting strains without transferable AR genes, coupled with monitoring and evaluation, is essential to minimise risks in aquaculture and food systems. Furthermore, interventions such as organic acid supplementation can support microbial safety and reduce potential virulence. This study provides an overview of the mechanisms and safety considerations associated with antibiotic resistance in seafood-derived probiotics, emphasising the importance of balancing functional benefits with public health and environmental safety considerations. The responsible selection and monitoring of probiotic strains is critical to their effective and safe application in aquaculture and functional food production.

Keywords: seafood probiotics, lactic acid bacteria, antibiotic resistance, food safety

Introduction

Antimicrobial resistance (AMR) has become one of the most critical global problems threatening human health, environmental sustainability, and food production systems. Population growth, urbanization, the rise of intensive production systems, and the uncontrolled use of antibiotics are accelerating the selection of resistant bacteria and leading to the increasing prevalence of multidrug-resistant (MDR) pathogens in the community, hospitals, and the food chain (1). This complicates the treatment of serious infections and poses high risks of mortality and economic losses to public health.

In recent years, the global aquaculture sector has become a major focus for AMR (2). World aquaculture production reached 185 million tons in 2022; this increase was largely fueled by intensive aquaculture systems relying on antibiotic applications (3). The uncontrolled use of antibiotics at subtherapeutic doses has created a strong selection pressure in aquatic environments, leading to the rapid spread of resistance genes (ARGs) through mobile genetic elements among microbial communities (4). This spread is not limited to aquatic microorganisms; an integrated resistance pool is forming among human, animal, and environmental reservoirs (5).

The factors that cause AMR are not limited to aquaculture. Urban wastewater, agricultural drainage, hospital effluents, livestock waste, and food processing plants are also important sources of ARG accumulation (6,7). The detection of high densities of Enterobacteriaceae in river and coastal ecosystems suggests that these water sources directly impact fish farms, increasing ARG levels (8). The transfer of resistant bacteria into the food chain poses a critical risk to consumer health. Food pathogens such as Salmonella, Escherichia coli, Campylobacter, Listeria monocytogenes, and Staphylococcus aureus have been reported to have developed resistance to many classes of antibiotics and are particularly prevalent in poultry, red meat, and seafood (9). Multicenter international studies have reported alarming levels of resistance to critical classes of antibiotics—third-generation cephalosporins, carbapenems, fluoroquinolones, and polymyxins (10). Therefore, the One Health Joint Action Plan published by WHO, FAO, WOAH, and UNEP emphasizes that the environmental, animal, and human components of AMR cannot be separated and that a multisectoral, holistic approach is essential (11).

The widespread use of metagenomic technologies has more clearly revealed the presence of pathogens with multiple resistance genes, particularly in aquaculture products (12). According to the MicroBIGG-E database, clinically critical ARGs such as β-lactamases (ESBL), carbapenemases (bla_NDM), colistin resistance (mcr), tigecycline resistance (tetX), and glycopeptide resistance (vanA) are prevalent worldwide in microorganisms isolated from fish and shellfish (8). These findings clearly demonstrate that AMR is no longer merely a clinical problem but a multidimensional crisis in terms of agricultural production, environmental sustainability, and global food security.

In this context, probiotics derived from seafood—especially lactic acid bacteria (LAB)—are widely used in aquaculture and functional foods (13). These microorganisms have beneficial effects such as pathogen inhibition, regulation of the intestinal microbiota, immune support, and improved product quality. Many LAB strains are considered GRAS (Generally Recognized as Safe) or QPS (Qualified Presumption of Safety) and are therefore considered safe (14). However, in recent years, it has been shown that some LAB strains carry intrinsic or acquired antibiotic resistance genes and that these genes can be transferred to other microorganisms via mobile genetic elements (EFSA, WHO). This poses a potential biosafety risk in the use of probiotics.

This review evaluates the mechanisms and prevalence of antibiotic resistance in seafood-derived probiotic strains, and the potential risks they pose to food safety, emphasizing the importance of safe strain selection, genomic characterization, and regulatory approaches. The aim is to offer an approach that minimizes the risk of spreading resistance genes while preserving the functional benefits of probiotics.

2. Antibiotic Resistance Mechanisms

Antibiotic resistance traits observed in probiotic bacteria isolated from seafood can be both intrinsic (natural) and acquired (via mobile genetic elements). Accurately identifying resistance mechanisms is critical for strain safety assessments. Three main mechanisms of antibiotic resistance are generally recognized: (i) enzymatic inactivation of antibiotics, (ii) modification or preservation of the target site, and (iii) cellular excretion of the antibiotic (efflux pumps) (15).

2.1. Enzymatic Inactivation

One of the best-defined mechanisms of antibiotic resistance in bacteria is enzymatic inactivation of the antibiotic. In this mechanism, enzymes encoded by resistance genes directly disrupt the structure of the antibiotic molecule or inactivate the drug by chemical modification. β-lactamases, aminoglycoside-modifying enzymes, and chloramphenicol acetyltransferases are particularly important in this group (16). β-lactamases hydrolyze the ring structure of β-lactam antibiotics, inactivating penicillin, cephalosporin, and monobactam classes of drugs; broad-spectrum variants, extended-spectrum β-lactamases (ESBL), have gained particular clinical importance by conferring high resistance to third-generation cephalosporins (17). Similarly, aminoglycoside phosphotransferases, adenyltransferases, and acetyltransferases chemically modify the hydroxyl or amino groups of aminoglycoside antibiotics, reducing their binding affinity and rendering ribosomal target sites inaccessible (18). Chloramphenicol acetyltransferases, on the other hand, acetylate the chloramphenicol molecule, preventing its binding to the ribosomal 50S subunit and inactivating the antibiotic. This enzyme is susceptible to horizontal gene transfer because it can be carried by both chromosomal genes and plasmids (19). These enzymatic resistance mechanisms have been reported not only in clinical pathogens but also in environmental and foodborne bacteria. Increasing evidence indicates the presence of ESBL genes, aminoglycoside-modifying enzymes, and chloramphenicol acetyltransferases, particularly in members of the Enterobacteriaceae and lactic acid bacteria isolated from marine environments (8). High antibiotic use in aquaculture environments creates strong selection pressure in the water column and sediment, accelerating the spread of genes encoding these enzymes via mobile genetic elements (5). Therefore, enzymatic inactivation not only reduces pharmacological efficacy but also poses a significant risk for resistance transmission in the food chain and probiotic applications.

2.2. Target Change and Protection

Many antibiotics act by binding to a specific molecular target in the cell, and the structural integrity of this target site is critical to the antibiotic's effectiveness. Resistance genes prevent antibiotic binding by altering or preserving the structure of this target site. One of the most common examples is point mutations in ribosomal proteins or ribosomal RNA regions. These mutations alter the binding sites of drugs that target protein synthesis, particularly macrolides, lincosamides, and streptogramins. In macrolide resistance, methylases encoded by erm genes sterically obstruct the antibiotic's binding pocket by methylating the 23S rRNA, which can lead to high-level resistance (20). Similarly, mutations or overexpression in penicillin-binding proteins (PBPs) targeting β-lactam antibiotics prevent the drug from binding to the

transpeptidase domain, and cell wall synthesis continues. This mechanism is well-defined in Staphylococcus and Enterococcus species, and even probiotic LAB strains have reported low-level β-lactam susceptibility due to intrinsic PBP differences (21).

Resistance to antibiotics targeting DNA replication, such as fluoroquinolones, most often arises from mutations in the DNA gyrase (gyrA) or topoisomerase IV (parC) genes. These mutations prevent the formation of the enzyme-antibiotic complex, allowing DNA supercoiling and replication to continue. This mechanism has been widely described in clinical pathogens, and low fluoroquinolone susceptibility has also been reported in lactic acid bacteria isolated from seafood (22).

These target-based resistance strategies are not limited to pathogenic microorganisms. There are discussions in the literature that probiotic LAB strains possess similar mechanisms and that these resistance traits may be mediated by horizontal gene transfer (23). Therefore, safety assessments of probiotic candidates should consider not only phenotypic susceptibility but also genomic analysis of target site mutations. Thus, the distinction between intrinsic and mobile gene-mediated resistance can be made clearly and the risks of ARG spread in the food chain can be managed more accurately.

2.3. Efflux Pump Activity

Efflux pumps are an important resistance mechanism that actively transports antibiotics out of cells, preventing effective intracellular accumulation. These systems operate via ATP-dependent transporters (ABC transporters) or proton-motive pumps and play a role in resistance, particularly to tetracycline and macrolide antibiotics (24). Although efflux pumps are generally associated with low-level resistance, when the genes encoding these pumps reside on mobile genetic elements such as plasmids or transposons, resistance can be transferred to different species, potentially leading to multidrug resistance. Therefore, the presence of an efflux mechanism is considered a parameter that should be carefully monitored in the biosafety assessment of probiotic strains isolated from seafood.

2.4. Mobile Genetic Elements: Plasmids, Transposons and Integrons

Acquired antibiotic resistance genes are often transmitted via mobile genetic elements (MGE). These elements include plasmids, transposons, integrons, and bacteriophages, and they facilitate gene exchange between bacterial species. This allows resistance genes to be transferred both from probiotic strains to potential pathogens and from environmental bacteria to the food microbiota (20). This process, which occurs through horizontal gene transfer, can facilitate the rapid spread of resistance genes and the development of multidrug resistance. Therefore, EFSA and WHO recommend the use of strains carrying antibiotic resistance genes carried on plasmids or transposons as probiotics, starter cultures, or feed additives, and recommend meticulous genomic screening and strain selection for safe applications.

Table 1. Antibiotic Resistance Mechanisms and Sample Genes in Seafood-Derived Probiotics

Resistance Mechanism	Detail	Example Resistance Genes / Enzymes	Related Antibiotics	References
Enzymatic inactivation	Degradation or chemical modification of the antibiotic	ESBL (bla_CTX-M), bla_NDM, CAT	β-lactams, aminoglycosides, chloramphenicol	16-18
Target change / preservation	Mutation or modification of the target site to which the antibiotic binds	mecA, gyrA, parC	β-lactams, fluoroquinolones	20-23
Efflux pumps	Antibiyotiğin hücre dışına aktif olarak atılması	tetA, mefA, ermB	Tetracyclines, macrolides	24
Mobile genetic elements	Transferable plasmid, transposon, integron carriage	Tn916, IS1216, Integron class 1	Multidrug resistance (MDR)	20

3. Prevalence of Resistance Genes in LAB Isolated from Seafood

In recent years, the number of studies evaluating the microbial safety profiles of lactic acid bacteria (LAB) isolated from seafood has increased significantly. These studies have shown that while many isolated strains possess probiotic properties, some may also possess single or multiple antibiotic resistance phenotypes. Resistance genes, particularly those carried on mobile genetic elements, pose a critical risk to food safety because they can be transferred to the environmental microflora or potential pathogens (20).

Phenotypic assessments have reported varying levels of resistance to tetracycline, erythromycin, chloramphenicol, streptomycin, and penicillin antibiotics in LAB strains recovered from seafood (25). These resistance patterns vary widely among species used as probiotics, such as Lactobacillus, Lactococcus, Enterococcus, and Pediococcus (26). Tetracycline and macrolide resistance, in particular, has been reported as the most common phenotype in many studies and has been found to be consistent with efflux pumps and ribosomal target switching mechanisms.

Molecular analyses frequently confirm the presence of specific antibiotic resistance genes (ARGs) in strains with observed phenotypic resistance. The most frequently detected genes in LAB isolated from seafood include tet(M), tet(S), tet(L) (tetracycline resistance), erm(B) and mef(A) (macrolide/erythromycin resistance), the bla family (β-lactam resistance), and cat (chloramphenicol resistance). Some of these genes, particularly tet(M) and erm(B), are noteworthy because they can be transferred between both probiotic LAB and pathogenic bacteria via conjugative elements (27).

Metagenomic data also support these findings. The MicroBIGG-E database shows that microorganisms isolated from fish and shellfish frequently carry clinically critical ARGs such as bla_NDM (carbapenemase), mcr (colistin resistance), tetX (tigecycline resistance), and vanA (glycopeptide/vancomycin resistance) (28). These genes are associated with reserve or last-resort antibiotics by the WHO and are of particular importance for the spread of resistance throughout the food chain. The isolation of strains carrying mcr and bla_NDM from seafood represents a significant public health risk (29).

Table 2. Major Resistance Genes in LAB Strains Isolated from Seafood

Type	Identified Resistance Genes	Transport Type (Plasmid/Transposon)	Most Resistant Antibiotics	References
Lactobacillus spp.	tet(M), erm(B)	Plasmid, Tn916	Tetracycline, Erythromycin	30
Enterococcus spp.	vanA, bla, tet(L)	Plasmid, Integron	Vancomycin, β-lactam	29
Pediococcus spp.	mef(A), cat	IS elements	Macrolides, Chloramphenicol	31
Lactococcus spp.	tet(S), erm(B)	Conjugative transpozone	Tetracycline, Macrolides	32

4. Regulation and Security

The safe use of seafood-derived probiotics is closely linked not only to their technological performance but also to the potential for the spread of antibiotic resistance genes (ARGs) they carry. Therefore, regulatory authorities have tightened evaluation criteria in recent years, explicitly limiting the use of strains carrying mobile ARGs in food or feed additives (29). The primary objective is to minimize potential risks to public health while preserving the functional benefits of probiotic applications. EFSA's QPS (Qualified Presumption of Safety) approach emphasizes three fundamental conditions for safety in probiotics: that the strains have no pathogenic potential, that they do not produce toxins, and that ARGs are not located on mobile genetic elements (29). While many lactic acid bacteria strains on the QPS list are considered safe, screening for ARGs at the strain level is mandatory, and resistance genes located on plasmids or transposons invalidate this status.

Similarly, the WHO and FAO recommend phenotypic antibiotic susceptibility testing, genomic analysis, and conjugation potential assessments for the safe use of probiotics (33). A critical point is that the presence of a resistance gene in a strain does not alone constitute a risk; the risk is determined by whether the gene is mobile. Therefore, current guidelines recommend the removal of strains carrying mobile ARGs from marketed products, fermentation starter cultures, and aquaculture feeds (29). In contrast, intrinsic and non-mobile resistance traits (e.g., vancomycin resistance in Lactobacillus rhamnosus) are generally considered safe and are not excluded from the QPS framework (34).

Modern safety assessments are no longer limited to phenotypic testing. Whole-genome sequencing (WGS) has become a key component of strain selection, enabling the detection of ARGs, mobility islands, conjugative plasmid regions, and virulence and toxin genes with high sensitivity (35). This approach enables the elimination of risky strains early in product development. Furthermore, the regulatory framework is not limited to production but also encompasses final product labeling, traceability, and post-market inspection. Labeling the species and strain name, reporting antibiotic resistance markers, and ensuring product traceability are among the recommended practices by the FAO/WHO (33). The current risk assessment approach is based on three key steps: screening for strains carrying mobile ARGs through genomic screening, confirmation through phenotypic antibiotic susceptibility testing, and assessment of conjugation/transformation potential. This multi-layered framework ensures that probiotic strains can be used without posing risks to both food safety and public health.

5. Risk Reduction and Future Strategies

The risks associated with antibiotic resistance in seafood-derived probiotic strains can be managed with multifaceted strategies to both preserve functional advantages and ensure public health safety. The current approach focuses on selecting strains free of mobile resistance genes, reducing antibiotic use, implementing alternative biotechnologies, and strengthening systematic surveillance programs, rather than banning probiotic applications (29).

Reducing antibiotic use in aquaculture systems is the first and fundamental step in reducing the risk of AMR. Limiting the use of antibiotics for prophylactic and growth-promoting purposes, administering them only after veterinary diagnosis and prescription, and restricting the use of critical antibiotics are consistent with current policies in many countries (36). This approach, when supported by water quality management, stocking density control, vaccination, and biosecurity practices, significantly reduces the need for treatment (5).

The most critical issue for probiotic use is the safety-based selection of strains. Modern probiotic development programs have made whole genome sequencing (WGS) analyses mandatory, in addition to phenotypic susceptibility testing. This method allows for the highly sensitive detection of mobile ARGs, plasmid regions, conjugative elements, virulence factors, and toxin genes, enabling the selection of safe strains (35). Organic acids, phytobiotics, and bacteriophages are increasingly being evaluated as alternatives to antibiotics in aquaculture and food systems. Organic acids and plant compounds suppress pathogens by lowering intestinal pH and do not exert resistance selection pressure (37). Bacteriophages, on the other hand, have been effective in controlling species such as Salmonella, Aeromonas, and Vibrio, exhibiting specific effects on target pathogens, and the potential for synergistic use with probiotics has been reported (38). For all these applications to be effective, surveillance and monitoring structures must be developed. Microbial monitoring in fish farms, hygiene control in processing facilities, end-product testing, and post-market traceability reduce the risk of transmission of resistant bacteria throughout the food chain. (39) Many countries are now expanding their national AMR monitoring programs to include seafood and foods containing probiotics.

Finally, risk reduction strategies need to be integrated not only at the production or clinical level but also at the environmental and societal levels. Coordination, data sharing, and regulatory harmonization among veterinary health units, food safety agencies, and public health authorities are critical for long-term success in AMR management (39). Future research priorities include standardized protocols for mobile ARG detection, genomic characterization of novel probiotic strains, phage-probiotic combinations, and large-scale metagenomic surveillance. These studies will lay a strong scientific foundation for both sustainable aquaculture and safe food systems.

6. Conclusion

Probiotic strains derived from seafood offer significant benefits such as pathogen inhibition, intestinal health support, and immune modulation in aquaculture and functional food production. These microorganisms enhance production performance, improve product quality, and are compatible with sustainable farming objectives. However, recent studies have shown that some probiotic strains may carry intrinsic or acquired antibiotic resistance genes (ARGs), and that these genes can be transferred to other microorganisms via mobile genetic elements. This presents a biosecurity risk that should be considered not only for the target organisms but also for the food chain and public health.

Resistance mechanisms can arise through various pathways, such as enzymatic inactivation, target modification, and efflux pumps. It is known that ARGs, particularly those carried via plasmids, conjugative transposons, and integrons, facilitate horizontal gene transfer. Therefore, the safe use of probiotic strains should be evaluated by focusing on the mobility potential of resistance genes. Current guidelines do not strictly recommend the use of strains containing mobile ARGs as probiotics, starter cultures, or feed additives. However, non-mobile strains with intrinsic resistance profiles can be safely administered with appropriate screening procedures.

In this context, phenotypic antibiotic susceptibility testing and whole-genome sequencing (WGS) have become integral parts of strain selection. WGS strengthens risk management by providing the ability to identify mobile ARGs, virulence factors, and conjugation islands with high sensitivity. Furthermore, reducing antibiotic use, environmental monitoring, organic acid and bacteriophage applications, competitive exclusion strategies, and biosafety protocols stand out as effective tools to reduce resistance selection in aquaculture systems.

In conclusion, seafood-derived probiotics have the potential to be safe and effective ingredients with appropriate strain selection and regulatory control. Striking a balance between functional benefits and microbial safety, consistent with the One Health approach, requires a holistic assessment of environmental, animal, and human health. Future work is expected to focus on standardized methodologies for mobile ARG screening, expanding metagenomic surveillance networks, and developing alternative biotechnological solutions. These efforts will contribute to global antimicrobial resistance management and establish a strong scientific basis for sustainable aquaculture and safe food production.

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ADANA İLİ MERKEZ İLÇELERİ SERACILIK İŞLETMELERİNİN GENEL ÖZELLİKLERİNİN DEĞERLENDİRİLMESİ*

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ÖZET

Dünya nüfusunun hızla artmasıyla birlikte insanlığın en önemli gündemi sağlıklı beslenme haline gelmiştir. Dünyada sağlık problemleri arasında yetersiz ve dengesiz beslenme, GDO'lu ürünlerin insan sağlığına olumsuz etkileri en önemli konular olarak karşımıza çıkmaktadır. Tüketilen besinlerin sağlıklı koşullarda yetiştirilmesi büyük önem arz etmektedir. Covid-19 pandemisi ile Dünya'da gıda sektörünün önemi bir kez daha anlaşılmıştır. Bununla birlikte tarımda seraların ve seracılık işletmeleri faaliyetlerinin artmasına neden olmuştur. Bu çalışma, Türkiye'de seracılığın yoğun olarak yapıldığı Adana İl'i merkez ilçelerindeki seracılık işletmelerinin ve işletmelerde bulunan seraların mevcut durumlarının belirlenmesi, yapısal yönden incelenmesi ve sorunların tespit edilerek çözüm önerilerinin geliştirilmesi amacıyla 2019-2020 yılları arasında yürütülmüştür. Araştırmada, Adana ili merkez ilçeleri Seyhan, Yüreğir, Sarıçam ve Çukurova'da bulunan sürekli ve ticari olarak yetiştiricilik yapılan, yapı özellikleri, üretilen ürünler ve üretim şekli yönünden birbirinden farklı, yöreyi temsil niteliğine sahip 27 adet seracılık işletmesi amaçlı örnekleme metoduyla seçilerek incelenmiştir. Çalışmanın yürütüldüğü seracılık işletmelerinin özelliklerinin belirlenmesi amacıyla yüz yüze anket çalışması, yerinde ölçümler ve fotoğraf çekimi gerçekleştirilmiştir. Araştırma sonucunda, incelenen seracılık işletmelerinin %11'inin arazi varlığının 10 da ve altında, %11'inin 11-20 da arasında, %49'unun 21-50 da arasında, %11'inin 51-100 da arasında, %18'inin 100 da'dan büyük olduğu belirlenmiştir. Araştırmanın yürütüldüğü seracılık işletmelerinin sahiplerinin %60'ının lisans ve lisansüstü eğitime sahip olduğu belirlenmiştir. Araştırma alanında seracılık işletmelerinde; %40'ında muz, %60'ında ise domates, çilek, üzümsü meyveler, hıyar, süs bitkileri ve ejder meyvesinin yetiştirildiği tespit edilmiştir. İşletme sahiplerinin eğitim düzeyinin yüksek olduğu seracılık işletmelerinin teknoloji kullanım düzeyinin daha yüksek olduğu ve modern bir yapıya sahip oldukları belirlenmiştir. Seracılık işletmelerinin nicelik ve niteliğinin artırılması; seracılık işletmelerin özelliklerini inceleyen, yapısal ve iklimsel yeterliliklerinin iyileştirilmesi için yapılacak çalışmalarla gerçekleştirilecektir. Sonuç olarak, seracılık işletmelerinin kurulacak bölgenin özelliklerine uygun olarak özel tasarlanmış seralarda yetiştiricilik yapması tavsiye edilmektedir.

Anahtar Kelimeler: Adana, Sera, seracılık işletmesi, sürdürülebilir tarım.

*Bu çalışma Emine Balı nın S.Ü. BAP Koordinatörlüğü tarafından 19201077 nolu proje ile desteklenen yüksek lisans tezinin bir kısmından üretilmiştir.

EVALUATION OF GENERAL CHARACTERISTICS OF GREENHOUSE ENTERPRISES IN CENTRAL DISTRICTS OF ADANA PROVINCE*

ABSTRACT

The rapid increase in the world population has made healthy nutrition one of humanity's most critical priorities. Among global health problems, inadequate and unbalanced nutrition, along with the negative effects of GMO products on human health, stand out as major concerns. Ensuring that all consumed food is produced under healthy conditions is therefore essential. The Covid-19 pandemic further emphasized the importance of the global food sector and led to a rise in greenhouse construction and greenhouse farming activities. This study was carried out between 2019 and 2020 in the central districts of Adana Province, where greenhouse cultivation is highly intensive in Turkey. The aim was to determine the current situation of greenhouse enterprises and their structures, identify their problems, and develop solution proposals. Using purposive sampling, 27 greenhouse enterprises engaged in continuous commercial production and representing the region in terms of structural characteristics, crop types, and production methods were selected from Seyhan, Yüreğir, Sarıçam and Çukurova districts. To identify enterprise characteristics, face-to-face interviews, on-site measurements and photographic documentation were conducted. The results indicated that 11 percent of the enterprises had land areas of 10 decares or less, 11 percent between 11 and 20 decares, 49 percent between 21 and 50 decares, 11 percent between 51 and 100 decares, and 18 percent larger than 100 decares. It was also found that 60 percent of greenhouse owners held undergraduate or graduate degrees. In the study area, 40 percent of the enterprises grew bananas, while 60 percent produced tomatoes, strawberries, berries, cucumbers, ornamental plants and dragon fruit. Enterprises owned by individuals with higher educational levels tended to use technology more effectively and maintained more modern greenhouse structures. Strengthening the number and quality of greenhouse enterprises depends on research that examines their characteristics and enhances their structural and climatic capacities. Therefore, it is recommended that greenhouse facilities be designed and constructed according to the specific environmental conditions of the regions in which they are established.

Keywords: Adana, Greenhouse, greenhouse business, sustainable agriculture

*This study was derived from a portion of Emine Balı's master's thesis, supported by the Selçuk University Scientific Research Projects (BAP) Coordination Unit under project number 19201077.

INTRODUCTION

Greenhouses are enclosed structures that provide regulated growing conditions, allowing fruit and vegetable production outside natural seasons through highly light-transmissive covering materials (Güllüler, 2007). They are defined as high-system covered environments that enable year-round cultivation and seedling production by operating climate-control systems independent of external weather conditions. These structures are constructed using materials with high light transmittance such as glass, plastic, and fiberglass and may also serve storage or demonstration purposes (Anonymous, 2001). Greenhouse cultivation is practiced in many regions across the world. Countries with advanced greenhouse technologies include the United States, the Netherlands, Japan, the United Kingdom, Belgium, France, Italy, Germany, Denmark, Sweden, and several Eastern European nations (Yağanoğlu, 2008).

In Turkey, greenhouse production began in the 1940s in Antalya through the establishment of glass greenhouses. Greenhouse cultivation experienced its least active period between 1940 and 1960 (Tüzel et al., 2005). The most rapid development occurred after the 1970s (Öneş, 1986). One of the primary drivers of this advancement was the replacement of costly glass coverings with polyethylene (PE), a lightweight, economical, and easy-to-apply plastic material (Çolak, 2002). Substantial increases in greenhouse areas took place between 1975 and 1985, and total greenhouse area expanded by 64.5% between 1990 and 1997 (Tüzel & Eltez, 1997; Sevgican, 2000). Although greenhouse cultivation experienced a contraction in 2001 due to economic recession, the overall expansion trend continued. As cold winters adversely affect open-field production, protected cultivation has gained importance. Parallel to Turkey's growing population, greenhouse activities have continued to accelerate. While Turkey's total protected cultivation area was 643,442 hectares in 2014, it reached 776,109 hectares in 2024. Due to the high construction costs of glass greenhouses, their share declined from 80,975 ha in 2014 to 55,945 ha in 2024. In contrast, the area covered by plastic greenhouses increased from 298,651 ha to 452,907 ha during the same period. In 2014, low and high tunnels in Turkey occupied 156,720 ha and 107,095 ha, respectively, while in 2024 these values shifted to 163,275 ha for low tunnels and 103,275 ha for high tunnels. During the COVID-19 pandemic in 2020, Türkiye's agricultural sector demonstrated rapid growth. As a result, the total greenhouse area reached 508,856 ha in 2024. The temperate climate zone remains the most suitable geographical region for greenhouse operations (Yağanoğlu, 2008).

Today, greenhouses are widely distributed globally. Worldwide greenhouse cultivation covers approximately 800,000 ha, with the majority located in Mediterranean countries. Of this total, 85% of greenhouse areas are covered with plastic materials, while 15% utilize glass coverings (Silleli et al., 2020). In Turkey, the total protected cultivation area amounts to 776,109 ha, consisting of 59% (452,907 ha) plastic greenhouses, 7% (55,949 ha) glass greenhouses, 21% (163,275 ha) low tunnels and 13% (103,978 ha) high tunnels (TÜİK, 2025a). This study was conducted to examine the general characteristics and adequacy of greenhouse enterprises in the central districts of Adana Province, a region where greenhouse cultivation is intensively practiced, and to identify existing problems while proposing potential solutions.

MATERIALS AND METHODS

This study was conducted between 2019 and 2020 in 27 greenhouse enterprises located in the central districts of Adana Province, namely Seyhan, Yüreğir, Sarıçam, and Çukurova. A face-to-face survey was administered to determine the general characteristics of the enterprises, while observations, measurements, and photographic documentation were utilized to further examine their structural features.

The research methodology consisted of two stages: fieldwork and office-based analysis. The field stage involved selecting enterprises, conducting face-to-face surveys, performing on-site studies within greenhouse facilities, and making preliminary evaluations of the collected data. The office stage focused on the detailed assessment and interpretation of the information obtained during fieldwork.

A standardized survey form was prepared to ensure consistency across all participating enterprises. The survey included questions on the general characteristics of the enterprises, the structural features of the buildings within them, production-related information, and the problems encountered by operators. Additionally, measurements, sketches, plan drawings, and photographs were collected to more accurately document and describe the structures and facilities within each greenhouse enterprise.

RESULTS AND DISCUSSION

General characteristics of greenhouse enterprises

This study was conducted in 27 greenhouse enterprises located in the central districts of Adana Province, namely Seyhan, Sarıçam, Yüreğir and Çukurova. The distribution of enterprises across districts is presented in *Table 1*. Among the investigated enterprises, 51% were located in Seyhan, 30% in Sarıçam, 15% in Yüreğir and 4% in Çukurova. The high number of greenhouse enterprises in Seyhan can be attributed to its extensive availability of agricultural land (TÜİK, 2025b). As of 2024, greenhouse activities in Sarıçam District cover an area of 999 da which is supported by the district's large total land capacity of 422,915 da (TÜİK, 2025c).

Table 1. Distribution of greenhouse enterprises in the study according to central districts of Adana Province

District	Number of Enterprises (n)	Percentage (%)
Seyhan	14	51
Sarıçam	8	30
Yüreğir	4	15
Çukurova	1	4
Total	**27**	**100**

The distance of the greenhouse enterprises from the center of Adana Province ranged from 0.5 to 40 km. It was determined that 15% of the enterprises were located less than 5 km from the provincial center and 77% were situated 5 to 30 km away. Within this group, 25% were located 5 to 20 km from the center, 22% were located 10 to 20 km away and 30% were situated 20 to 30 km from the provincial center. Additionally, 8% of the enterprises were located more than 30 km away, with distances reaching up to 40 km. Greenhouses should ideally be established in easily accessible areas and distant from noisy environments (Hakgören & Kürklü, 2004).

The distance of the investigated enterprises to the nearest main road ranged from 0 to 13 km. Since these enterprises were located in central districts, transportation was generally convenient. Thirty-three percent of the enterprises (numbers 9, 11, 12, 13, 16, 24, 25, 26 and 27) were situated less than 0.5 km from a main road. Only one enterprise was found to be 13 km away from the nearest road. Excessive distance from main roads may lead to problems such as limited access, difficulty obtaining emergency support and potential damage to transport vehicles due to poorly maintained routes. Therefore, greenhouse enterprises should be

established in locations with easy access to main roads and nearby settlements. Uğurlu and Uzal Seyfi (2010) similarly reported that locating greenhouses close to main roads and settlements facilitates transportation and marketing. According to the *"Covered Agriculture Registration System Regulation,"* greenhouses must be established near secondary or main roads (Anonymous, 2014).

Sources of project financing among the greenhouse enterprises were classified as self-funded, publicly supported and leased enterprises. Of the investigated enterprises, 67% were established with the owner's own capital and project initiative, 22% were supported through public funding and 7% were financed through a combination of public support and personal capital. Only one enterprise was identified as leased. Financing structure plays a critical role in greenhouse establishment. In this study, publicly supported greenhouses were observed to be more professionally constructed, whereas self-funded enterprises tended to minimize costs and consequently built greenhouses with inadequate equipment and workmanship. Güllüler (2007) reported that greenhouse operators in Adana Province frequently attempted to reduce installation expenses by avoiding engineering services, deviating from appropriate plans and having greenhouses constructed by metalworkers lacking expertise in greenhouse structures. Similar practices were identified in this study.

It was also observed that greenhouses established through a combination of public support and personal capital possessed more professionally designed plans and construction projects. Conversely, many self-funded greenhouses were found to be technologically insufficient and lacked automation systems. Güllüler (2007) likewise noted that non-professional construction practices were common in Adana due to attempts to reduce initial investment costs.

Table 2. Project financing sources of the investigated greenhouse enterprises

Establishment Type	Source of Project	Number (n)	Percentage (%)
Self-funded	Based on his/her own idea	18	67
Public-supported	Public project	6	22
Leased	Based on his/her own idea	1	4
Public + self	Based on his/her own idea	2	7
Total		**27**	**100**

The establishment years of the investigated enterprises ranged from 1989 to 2020. Eleven percent of these enterprises (numbers 7, 12 and 22) were established in 1990 or earlier (1980 and 1989). No enterprises were founded between 1991 and 2000. It was determined that 85% of the enterprises were established between 2001 and 2020, and only one enterprise was founded after 2020. Owners of older greenhouses reported that renovation was needed but could not be carried out due to high costs. Greenhouses established after 2010 were observed to be more technologically advanced and equipped with improved automation systems.

The land size of the investigated greenhouse enterprises ranged from 8 to 260 da (Table 3). The average land size was 61.30 da, while the average greenhouse area was 9.76 da. Eleven percent of the enterprises had less than 10 da, 11% had 11 to 20 da, 11% had 51 to 100 da and 11% had 101 to 150 da. Nearly half of the enterprises (49%) had land areas between 21 and 50 da. During interviews, enterprise owners stated that they wished to expand their production areas and increase greenhouse capacity.

Table 3. Distribution of Greenhouse Enterprises by Land Size

Land Size (da)	Number (n)	Percentage (%)
≤10	3	11
11–20	3	11
21–50	13	49
51–100	3	11
101–150	3	11
>150	2	7
Total	**27**	**100**

The education levels of the enterprise owners were determined as follows: 15% had primary education, 22% had secondary education, 59% held undergraduate degrees and 4% held postgraduate degrees (Figure 1). Higher education among enterprise owners was found to contribute to a more professional outlook, the employment of qualified personnel and the application of more informed agricultural practices. Many of the owners with undergraduate degrees were agricultural engineers with the necessary expertise in plant production and cultivation. Their involvement was observed to positively influence agricultural practices within the region. Emekli (2007), in a study conducted in the Kumluca District of Antalya, similarly noted that increased producer awareness led to more informed agricultural practices and contributed to improved greenhouse activities. These findings emphasize the importance of expertise in greenhouse cultivation.

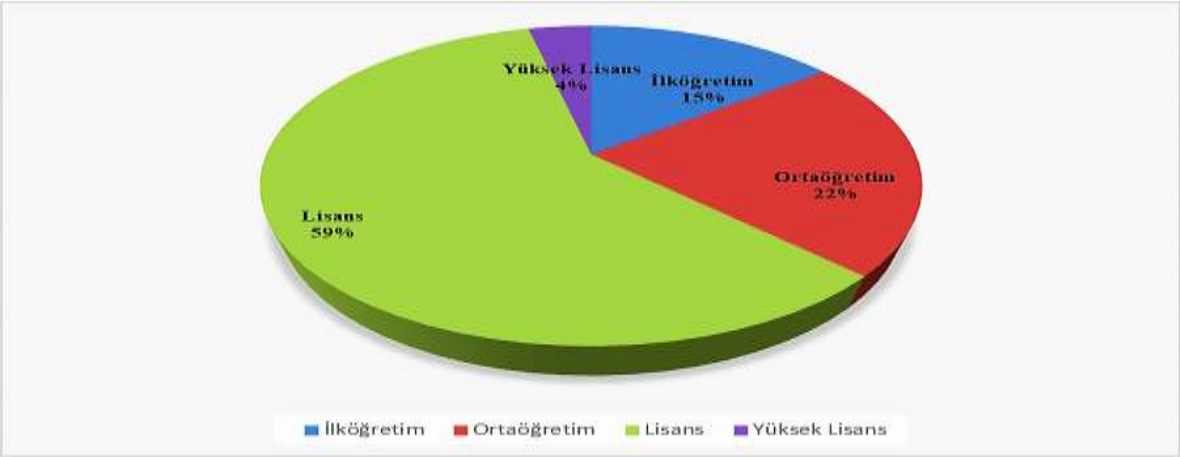

Figure 1. Educational status distribution of greenhouse enterprise owners

The number of personnel employed in the greenhouse enterprises examined in this study ranged from 1 to 48 individuals. In 41% of the enterprises, the number of employees was 1 or 2; in 34% it ranged between 3 and 10; in 11% it ranged between 16 and 20; and in 7% of the enterprises, the total number of workers was 48. The number of workers in greenhouse enterprises varies according to production intensity and enterprise size. The findings indicated that daily wage practices are still in use in greenhouse operations. Among the examined enterprises, both full-time personnel and workers residing overnight on site as guards were identified.

The working hours of employees in the investigated greenhouse enterprises were generally similar, typically ranging between 07:30 and 17:00, 07:00 and 17:30, or 08:00 and 18:00.

Table 4. Distribution of greenhouse enterprises by number of employees

Number of Employees	Number of Enterprises (Units)	Percentage (%)
<3	11	41
3–6	6	23
7–10	3	11
11–15	–	0
16–20	3	11
21–25	2	7
>25	2	7
Total	**27**	**100**

It was observed that the greenhouse enterprises examined in the study primarily grew bananas (15 enterprises) and also cultivated tomatoes, cucumbers, strawberries, berry fruits and dragon fruit. Additionally, 22% of the enterprises were engaged in seedling production, while 19% were established for demonstration purposes. In the greenhouses where seedling production was carried out, various seedlings including tomato, pepper, eggplant, cucumber, lettuce, watermelon and melon were produced. It was determined that only one greenhouse was established for research purposes, specifically for breeding activities. In this enterprise, ornamental plant production was also undertaken alongside breeding studies. Furthermore, it was observed that only one greenhouse was used for exhibition purposes.

Table 5. Distribution of the ınvestigated greenhouse enterprises by establishment purpose

Establishment Purpose	Number of Enterprises (Units)	Percentage (%)
Seedling Production	6	22
Cultivation	15	55
Research (Breeding)	1	4
Exhibition	5	19
Total	**27**	**100**

The marketing of products produced in the examined greenhouse enterprises was carried out through four main methods: direct sales from the greenhouse (retail), storage in cold rooms, wholesale and export. Direct sales referred to the purchase of ornamental plants directly from the greenhouse by customers. Storage in cold rooms was applied in banana-producing enterprises, enabling products to be marketed at more profitable prices during periods of low banana supply. Wholesale marketing occurred when buyers purchased all or a large portion of production either by placing an order or by visiting the enterprise. Export involved the sale of the entire greenhouse output to foreign markets.

Among the enterprises studied, 49% of products were marketed through wholesale channels, 40% through direct sales at the greenhouse and 7% through cold storage. Due to the perishable nature of certain products such as seedlings and bananas, their storage and preservation are challenging, requiring rapid marketing and delivery to consumers (Çimen, 2001).

Table 6. Distribution of the ınvestigated greenhouse enterprises by product marketing system

Product Marketing System	**Number of Enterprises (Units)**	**Percentage (%)**
Direct sales from greenhouse (retail)	11	40
Storage in cold rooms	2	7
Wholesale	13	49
Export	1	4
Total	**27**	**100**

Recommendations

The beginning of the new century has brought increasing emphasis on agricultural systems in which seeds are produced under certified conditions, measures are taken against diseases and pests, safe and clean food is ensured, climate control and energy resources are efficiently managed, and environmentally friendly production methods are adopted. As a result, sustainability has emerged as a key parameter for both environmental protection and human health. Ensuring that food is produced under optimal conditions highlights the importance of greenhouse enterprises, which make year-round agricultural production possible.

The need for greenhouse enterprises to operate in structurally adequate, modern facilities with a high level of technological integration has therefore increased. Ultimately, greenhouse cultivation in the Adana Region contributes substantially to both regional and national economic development. For this reason, it is recommended that greenhouse enterprises adopt cultivation practices in specially designed structures suited to the environmental characteristics of the regions in which they are established.

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KONYA İLİ VE İLÇELERİNDEKİ YUMURTA TAVUKÇULUĞU İŞLETMELERİNDEN KAYNAKLI KARBON SALINIMI YOĞUNLUK HARİTASININ TİER 1 METODU İLE OLUŞTURULMASI*

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ÖZET

Son yıllarda iklim değişikliği ve küresel ısınmaya neden olan karbon ayak izinin etkileri oldukça önemli bir konudur. Hayvancılık sektöründe faaliyet gösteren işletmelerde üretimden, enerji kullanımından ve gübre yönetiminden kaynaklı karbon salınımları gerçekleşmektedir. Bu salınımların sebep olduğu etkilerin bilinmesi, oluşabilecek zararlı etkilerin ortadan kaldırılması veya azaltılmasına yönelik uygulamaların geliştirilmesi; çevrenin korunması ve hayvancılık faaliyetlerinin daha sağlıklı yürütülebilmesi açısından oldukça önemlidir. Bu araştırma, Türkiye'de yumurta tavukçuluğu yetiştiriciliğinde 3. Sırada yer alan Konya bölgesinde faaliyet gösteren yumurta tavukçuluğu işletmelerinden kaynaklı karbon ayak izi değerlerinin IPCC yaklaşımına göre TİER1 Metodu kullanılarak hesaplanması ve toplam karbondioksit salınım değerlerinin yoğunluk haritasının oluşturulması amacıyla, 2023-2024 yılları arasında Konya Bölgesinde yürütülmüştür. Araştırmada, Konya Bölgesinde faaliyet gösteren tüm yumurta tavukçuluğu işletmelerinden kaynaklı karbon ayak izi değerlerinin Uluslararası İklim Değişikliği Paneli (IPCC) yaklaşımına göre TİER1 Metodu kullanılarak hesaplanması için; Konya Bölgesinde bulunan tavukçuluk işletmelerinin envanteri çıkarılmıştır. İlgili Kamu ve özel kuruluşlarla görüşülerek Bölgede faaliyet gösteren yumurta tavukçuluğu işletmelerine ait veriler (işletme özellikleri, kümes planlama sistemleri, hayvan sayıları, gübre yönetim uygulamaları...) alınmıştır. TİER metotları kullanılırken IPCC 2023 kılavuzunda yer alan Türkiye'nin ve araştırmanın yürütüldüğü Konya bölgesinin iklim özellikleri, hayvan türü, üretim verimliliği ve gübre yönetimi gibi işletmenin ve hayvancılık faaliyetlerinin özelliklerine göre önerilen değerler kullanılarak hesaplanmış, işletmelere ve işletmelerdeki hayvanlara ait karbon ayak izi miktarları belirlenerek, araştırma bölgesi olan Konya İli ve İlçeleri için detaylı karbondioksit salınımı (küresel ısınma potansiyeli) yoğunluk haritası oluşturulmuştur. Konya Bölgesinde (İli ve ilçeleri) 7,25 milyon adet yumurta tavuğundan kaynaklanan yıllık toplam 4.5 Gg (4,5 milyon kg) CO_2e salınımı (CH_4: %57; N_2Odirect: %18,7; N_2Ouçucu hale gelme: %36) değerleri hesaplanmıştır. Araştırma sonucunda Konya Bölgesindeki yumurta tavukçuluğu işletmelerinin tamamında yetiştirilen hayvanlar dikkate alınarak TİER1a metoduna göre karbon ayak izi; 0,62 kg CO_2e /tavuk, 4,13 kg CO_2e /kg gübre olarak hesaplanmıştır. Konya bölgesi için 2024 yılına ait küresel ısınma potansiyeli yoğunluk haritası oluşturulmuştur. Konya Bölgesinde 2024 yılı yumurta tavukçuluğu işletmelerinin gübre yönetiminden kaynaklı yaklaşık 4,5 Gg CO_2/yıl salınım gerçekleştiği hesaplanmıştır. Konya Bölgesinde Karatay, Meram, Kulu, Selçuklu, Akşehir ilçelerinin yumurta tavukçuluğu yetiştiriciliğinden kaynaklı CO_2 salınım miktarlarının yüksek olduğu belirlenmiştir.

Anahtar Kelimeler: Karbon ayak izi, karbon salınımı, Konya, yumurta tavukçuluğu.

*Bu çalışma Yasemin KOCAMAN'ın doktora tezinin bir kısmından üretilmiştir.

CONTRUCTION OF A CARBON EMISSION DENSITY MAP FOR LAYER HENS FARMS IN KONYA PROVINCE AND ITS DISTRICTS VIA THE TIER 1 METHODOLOGY*

ABSTRACT

In recent years, the impacts of the carbon footprint, which causes climate change and global warming, have become a subject of significant importance. In livestock enterprises, carbon emissions occur due to production processes, energy consumption, and manure management. Understanding the effects of these emissions and developing practices to eliminate or mitigate potential adverse impacts is crucial for environmental protection and ensuring the sustainable operation of livestock activities. This study was conducted in the Konya region, which ranks third in egg-layer poultry production in Turkey, between 2023 and 2024. The objective was to calculate the carbon footprint values originating from egg-layer poultry enterprises in the region using the TIER1 Method according to the IPCC approach and to create a density map of the total carbon dioxide emissions. For this purpose, an inventory of poultry operations in the Konya region was compiled. Data pertaining to the egg-layer poultry enterprises operating in the region (including enterprise characteristics, housing systems, animal numbers, and manure management practices) were obtained through consultations with relevant public and private institutions.The calculations employing the TIER methods utilized the default values recommended in the IPCC 2023 guidelines, which are specific to the climatic conditions of Turkey and the Konya region, as well as the characteristics of the enterprises and livestock practices, such as animal type, production efficiency, and manure management. The carbon footprint quantities for the enterprises and their animals were determined, and a detailed carbon dioxide emission (global warming potential) density map was created for the Konya province and its districts, which constituted the research area. The calculations for the Konya region (the province and its districts) estimated an annual total emission of 4.5 Gg (4.5 million kg) of CO_2e originating from 7.25 million egg-laying hens. The contribution of various gases to this total was calculated as follows: CH_4: 57%; direct N_2O: 18.7%; and N_2O from volatilization: 36%. The study found that, considering all animals reared in the egg-layer poultry enterprises across the Konya region, the carbon footprint according to the TIER1a method was calculated as 0.62 kg CO_2e per bird and 4.13 kg CO_2e per kg of manure. A global warming potential density map for the year 2024 was generated for the Konya region. It was determined that manure management in the region's egg-layer poultry enterprises resulted in approximately 4.5 Gg CO_2e per year. The districts of Karatay, Meram, Kulu, Selçuklu, and Akşehir were identified as having high CO_2 emission levels due to egg-layer poultry farming.

Keywords: Carbon footprint, Carbon emissions, Konya, Egg poultry farming.

*This study was derived from a portion ofYasemin KOCAMAN’s pHD Thesis.

INTRODUCTION

The impact of human activities on nature has increased since the Industrial Revolution. The intensive use of fossil fuels in areas such as energy consumption, transportation, agriculture, and industry leads to significant greenhouse gas emissions into the atmosphere. In this context, the "carbon footprint" concept has emerged as a crucial tool for measuring and managing environmental impacts.

The carbon footprint concept is a metric, typically calculated in carbon dioxide (CO_2) equivalent, that measures the direct and indirect greenhouse gas emissions released into the atmosphere by individuals, institutions, or activities. As a key indicator in the fight against global climate change, the carbon footprint plays a critical role in achieving sustainability goals, particularly in agricultural activities.

Global warming, on the other hand, is the process whereby greenhouse gases (CO_2 and CH_4) accumulating in the atmosphere due to human activities artificially increase the planet's temperature (UN, 1992; IPCC, 2021). The increase in the concentration of these gases in the atmosphere is the primary cause of rising global temperatures. On farms, the *"carbon footprint",* expressed in CO_2 equivalent, is a measure of the damage caused by greenhouse gases resulting from fossil fuel use and human activities, quantified in units of carbon dioxide (Wiedmann and Minx, 2008; Kılıç and Amet, 2017).

In Turkey, studies on carbon footprint calculations and management have gained increasing momentum in recent years within the scope of the global fight against climate change. In this direction, legal regulations for monitoring, reporting, and reducing greenhouse gas emissions have been implemented by relevant public institutions, primarily the Ministry of Environment, Urbanization and Climate Change. Particularly with the *"Regulation on the Monitoring of Greenhouse Gas Emissions"* enacted in 2014, high-capacity enterprises were obligated to report their emissions, thereby establishing an institutional infrastructure for determining and managing the national carbon footprint (ÇŞİDB, 2014).

In sectors with high emission potential, such as industry, energy, transportation, and agriculture, voluntary carbon footprint calculations are conducted in accordance with international standards like ISO 14064 and the GHG Protocol. Furthermore, preparations for the establishment of the Turkish Emission Trading System (ETS) are ongoing, with the aim of integrating it into carbon market mechanisms (ISO, 2018).

The global number of egg-laying hens, based on 2023 data taken from FAO (2025), is presented in Table 1.1. The total number of egg-laying hens worldwide has reached 27.2 billion. Among these, China ranks first with approximately 5.2 billion hens (19.16%), constituting about one-fifth of the global total. It is followed by Indonesia (3.7 billion) and Pakistan (1.88 billion). Turkey, with 368.6 million hens, ranks 11th, possessing 1.35% of the world's chicken population. Turkey's chicken population places it among the developed countries and indicates a significant production capacity in the sector.

When all these data are evaluated together, it is observed that while Konya Province continues to play a strategic role in egg-laying chicken farming in Turkey, its relative importance within total poultry farming has decreased. This situation indicates that regional production dynamics, investment trends, and structural transformations in the sector have had varying impacts in different provinces. Furthermore, the production contraction experienced by Konya, especially after 2020, points to a process that needs to be addressed with more comprehensive analyses at the environmental, economic, or sectoral level.

This research was conducted to calculate the carbon footprint values originating from egg-laying hen operations in the Konya region using the TIER 1 Methodology according to the IPCC approach and to create a density map of the total carbon dioxide emission values.

MATERIALS AND METHODS

Konya Province is the largest province in Turkey by surface area, covering 38,873 km² (HGM, 2025). It is located in the southern part of the Central Anatolia Region, within the Konya subregion. Its southern and southwestern sections fall within the Mediterranean Region. The lands of Konya stretch across vast plains situated among the high mountains of Central Anatolia. The province is positioned between 36°41'–39°16' north latitude and 31°14'–34°26' east longitude, with an average elevation of 1,016 meters. It features a climate characterized by hot and dry summers and rainy winters (KİKTM, 2024).

According to the Address-Based Population Registration System, the population of Konya in 2024 is 2,330,024, constituting 2.7% of Turkey's population (85,664,944). In a comparison among provinces, Konya is the 6th largest city in Turkey by population. The population growth rate is increasing at a rate of 0.42%. With a surface area of 38,873 km², Konya is the largest city in Turkey. The population density is 59 persons per square kilometer (Anonymous, 2025c).

Konya Province is administratively composed of 31 districts. Numerous natural lakes and marshes are located within the provincial boundaries. Lake Tuz (Salt Lake), situated at the intersection of Konya, Ankara, and Aksaray provinces, is one of Turkey's significant salt sources. Lake Beyşehir is Turkey's third-largest and largest freshwater lake; it is of tectonic-karstic origin and holds national park status. Lake Suğla, located in the southwest of Konya, has fresh water and is important for irrigation and fisheries. Additionally, Lake Ilgın (Çavuşçu), Ereğli Akgöl, and Yunak Akgöl are other significant lakes within the province (KİKTM, 2024).

Due to its location in the Central Anatolia Region, Konya Province exhibits typical continental climate characteristics. Climatic data for Konya Province (for the years 1929-2025) is provided in Table 3.2. According to long-term averages for Konya Province, the mean annual temperature is 11.8°C, while the highest average temperature occurs in July and August at 30.2°C, with the absolute maximum temperature recorded as 40.9°C in August. The long-term average lowest temperature in the province is -4°C in January, and the absolute minimum temperature average is -8.2°C, also in January. The mean annual total precipitation is 327.6 mm, with the highest precipitation measured in May at 43.5 mm.

Türkiye's poultry inventory is presented in Table 1. The total poultry population in Turkey, according to 2024 data, is 384 million birds (TRGM, 2025). Konya Province's laying hen population is 7.25 million, which constitutes 6.65% of Turkey's total laying hen population of 109.1 million. According to 2024 data, the total poultry population in Turkey is 384.1 million birds. In Turkey, the number of laying hens is 109.1 million, while the number of broiler chickens is 270.5 million (TRGM, 2025). This situation indicates that Konya Province holds a significant position in the national capacity for commercial egg and broiler production.

Table 1. Poultry Population in Turkey, 2024 (TRGM, 2025)

Poultry Type	Number of Birds (head)	Percentage (%)
Broiler Chicken	270.526.611	70.42
Laying Hen	109.100.202	28.40
Turkey	2.826.858	0.74
Goose	1.303.026	0.34
Duck	389.957	0.10
Total Poultry (head)	384.146.654	100

Within Turkey's total poultry inventory, the largest share belongs to broiler chickens, with a 70.42% rate and 270 million birds (Table 1). Laying hens, with 109 million birds, constitute 28.40% of Turkey's total poultry inventory and represent the second largest poultry group in the sector. Among other poultry species: turkeys, with 2.8 million birds, account for 0.74% of Turkey's total poultry; geese, with 1.3 million birds, account for 0.34%; and ducks, with 389 thousand birds, account for 0.10%.

In determining the carbon footprint, while the Tier 1 method is generally used, if country-specific productivity parameters are available for the studied livestock type, the Tier 1a method is used instead of Tier 1 (IPCC, 2019).

$$CH_{4(mm)} = \left[\sum_{T,S,P} \left(N_{(T,P)} \bullet VS_{(T,P)} \bullet AWMS_{(T,S,P)} \bullet EF_{T,S,P} \right) / 1000 \right]$$

$CH_{4(mm)}$=[[$N_{(T,P)}$ * $VS_{(T,P)}$ * $AWMS_{(T,S,P)}$ * $EF_{(T,S,P)}$]/1000]

$CH_{4(mm)}$= CH_4 emissions from Manure Management in the country, kg CH_4 yr^{-1}

$N_{(T,P)}$= number of head of livestock species/category *T* in the country, for productivity system *P*, when applicable

$VS_{(T,P)}$ = annual average VS excretion per head of species/category *T*, for productivity system *P*, when applicable in kg VS $animal^{-1}$ yr^{-1} (Table 10.13a calculated by Equation 10.22a, IPCC, 2019)

$AWMS_{(T,S,P)}$= fraction of total annual VS for each livestock species/category *T* that is managed in manure management system *S* in the country, for productivity system *P*, when applicable; dimensionless, default regionally specific AWMS fractions are found in Tables 10A.6 through 10A.9 in Annex 10A.2 , IPCC, 2019)

$EF_{(T,S,P)}$ = emission factor for direct CH4 emissions from manure management system *S,* by animal species/category *T*, in manure management system *S*, for productivity system *P*, when applicable (Table 10.14), g CH_4 kg VS^{-1}

S = manure management system

T = species/category of livestock

P = high productivity system or low productivity system for use in advanced Tier 1a – omitted if using a simple Tier 1 approach

$$N_2O_{D(mm)} = \left[\sum_S \left[\sum_{T,P} \left((N_{(T,P)} \bullet Nex_{(T,P)}) \bullet AWMS_{(T,S,P)}\right) + N_{cdg(s)}\right] \bullet EF_{3(S)}\right] \bullet \frac{44}{28}$$

$N_2O_{Direct(mm)}$ = [[($N_{(T,P)}$ * $Nex_{(T,P)}$) * $AWMS_{(T,S,P)}$) + $N_{cdg(s)}$] * $EF_{3(S)}$] * (44/28)

$N_2O_{Direct(mm)}$ = Direct N_2O emissions from Manure Management in the country, kg N_2O yr^{-1}

$N_{(T,P)}$= number of head of livestock species/category *T* in the country, for productivity system *P*, when applicable

$Nex_{(T,P)}$= annual average N excretion per head of species/category *T* in the country, for productivity system *P*, when applicable in kg N $animal^{-1}$ yr^{-1}

$N_{cdg(s)}$ = annual nitrogen input via co-digestate in the country, kg N yr^{-1}, where the system (s) refers exclusively to anaerobic digestion

AWMS(*T,S,P*) = fraction of total annual nitrogen excretion for each livestock species/category *T* that is managed in manure management system *S* in the country, dimensionless; to consider productivity class *P*, if using a Tier 1a approach

$EF_{3(S)}$= emission factor for direct N_2O emissions from manure management system *S* in the country, kg N_2O-N/kg N in manure management system *S*

S = manure management system *S*

T = species/category of livestock *T*

P = productivity class, high or low, to be considered if using the Tier 1a approach *P*

44/28 = conversion of N2O-N(mm) emissions to N2O(mm) emissions

$$N_{volatilization-MMS} = \sum_S \left[\sum_{T,P} \left[\left(\left(N_{(T,P)} \bullet Nex_{(T,P)}\right) \bullet AWMS_{(T,S,P)}\right) + N_{cdg(s)}\right) \bullet Frac_{GasMS(T,S)}\right]\right]$$

$N_{volitilization-MMS}$ = [[($N_{(T,P)}$ * $Nex_{(T,P)}$) * $AWMS_{(T,S,P)}$) + $N_{cdg(s)}$] * $Frac_{GasMS(T,S)}$]

N volatilization-MMS = amount of manure nitrogen that is lost due to volatilisation of NH3 and NOx, kg N yr^{-1}

$N_{(T,P)}$= number of head of livestock species/category *T* in the country, for productivity system *P*, when applicable

$Nex_{(T,P)}$= annual average N excretion per head of species/category *T* in the country, for productivity system *P*, when applicable in kg N $animal^{-1}$ yr^{-1}

$N_{cdg(s)}$ = annual nitrogen input via co-digestate in the country, kg N yr^{-1}, where the system (s) refers exclusively to anaerobic digestion

AWMS(*T,S,P*) = fraction of total annual nitrogen excretion for each livestock species/category *T* that is managed in manure management system *S* in the country, dimensionless; to consider productivity class

$Frac_{GasMS(T,S)}$ = fraction of managed manure nitrogen for livestock category *T* that volatilises as NH_3 and NOx in the manure management system

In this research, following the IPCC approach for determining the carbon footprint, the Tier 1a method was used to determine the carbon footprint originating from laying hen operations in Konya Province and its districts, as well as the CH_4 and N_2O emissions from manure at these operations. A density map of the total CO_2 emissions originating from laying hen operations in Konya Province and its districts was created using the ArcGIS (ESRI) software.

RESULTS AND DISCUSSION

According to 2024 data obtained from the Provincial Directorate of Agriculture and Forestry, Statistics Branch Directorate, the number of chickens in layer hen enterprises across Konya's 31 districts and the preference for the cage system as the rearing method have been determined. The calculations for the enterprises were performed using the Tier 1a methodology, selecting the high-productivity class option. The cage system was chosen for these calculations because, in Konya Province, only 3% to 5% of the layer hen operations are free-range systems with litter; the manure management scenario assumed that manure was sent to a biogas plant every two days.

Tier 1a: Determination of the CO_2 Emission Map Calculated for Konya Province and its 31 Districts

The layer hen population calculated for the 31 districts of Konya Province was converted into annual CO_2 emissions using typical emission coefficients for high-productivity cage system operations. The map reveals a variation in emission quantities, ranging from low-capacity enterprises (Taşkent, Ahırlı, Halkapınar, Derbent, Derebucak) to very high-capacity integrated production regions (e.g., Karatay, Meram, Kulu, Selçuklu, Sarayönü, Çumra, Altınekin).

The map displays the CO_2 emissions calculated based on the layer hen population in the districts of Konya Province. According to the color scale on the map, darker-colored districts represent high carbon emissions, while lighter-colored districts represent low carbon emissions. The carbon emission map for the Konya region for the year 2024 is provided in Figure 1. The layer hen population calculated for the 31 districts of Konya Province was converted into annual CO_2 emissions using typical emission coefficients for high-productivity cage system operations. The map reveals a variation in emission quantities, ranging from low-capacity enterprises (Taşkent, Ahırlı, Halkapınar, Derbent, Derebucak) to very high-capacity integrated production regions (e.g., Karatay, Meram, Kulu, Selçuklu, Sarayönü, Çumra, Altınekin).

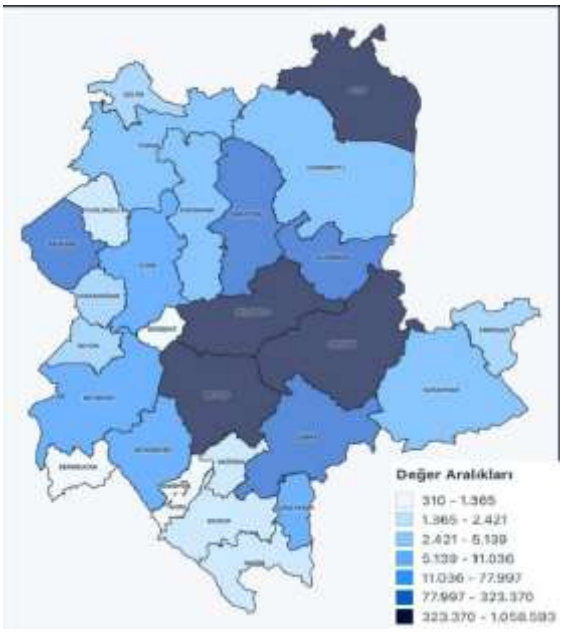

Figure 1. Carbon Emission Map for the Year 2024, Showing the 31 Districts of Konya Province.

Karatay (1,705,560 hens, 1,058,593 kg CO_2/year), Meram (1,536,500 hens, 953,662 kg CO_2/year), and Kulu (1,315,890 hens, 816,736 kg CO_2/year) are depicted in the darkest shade, indicating the districts with the highest carbon density in Konya. They are followed by Selçuklu, Sarayönü, and Çumra, which also stand out as significant emission centers due to the concentration of high-capacity cage system operations. Districts with medium tones, such as Altınekin, Güneysınır, Ereğli, and Akşehir, are areas with medium-capacity enterprises and moderate CO_2 emissions. In contrast, districts marked in the lightest shade, such as Taşkent, Ahırlı, Halkapınar, Derebucak, and Bozkır, are notable for their very low carbon emission values, owing to the prevalence of small-capacity enterprises. The overall total for Konya Province is approximately 4.5 Gg CO_2/year (4.5 million kg) produced from 7.25-million-layer hens. This distribution shows that emission density is higher in the dark-colored centers and that mitigation policies should be prioritized in these regions.

Tier 1a: CH_4 Emissions from Manure Management

For Regarding the laying hen farming activities carried out in 31 districts of Konya province, the manure management system value for the enterprises was taken as the amount of manure that has left the poultry house—either stored for transport to "Anaerobic Digestion - Biogas" biogas plants or used as fuel. For the manure management system to be calculated within the poultry houses, the Animal Waste Management System (AWMS) value of "Other (Poultry manure with litter)" for the laying hen animal category in the Eastern Europe region was taken as 19%. In the calculations, it was observed that methane (CH_4) emissions originating from manure management showed significant variation across districts.

As presented in Table 2, the laying hen population in the districts of Konya province and the resulting annual methane (CH_4) emission amounts and carbon dioxide (CO_2) equivalents are demonstrated.

The analysis of annual CH_4 emissions conducted across Konya Province calculated a total of 94,348.47 kg CH_4 emissions from 7,253,446 layer hens in 31 districts. Using the IPCC's 100-year global warming potential multiplier (GWP_{100} = 27 kg CO_2e/kg CH_4), a carbon equivalent of 2,547,408.78 kg CO_2e/year was obtained.

The emission distribution on a district basis is concentrated in Karatay (598,992.33 kg CO_2e; 23.3%), Meram (539,618.49 kg CO_2e; 21.0%), and Kulu (462,140.30 kg CO_2e; 18.0%), with these three districts alone accounting for approximately 62.3% of the total emissions. The average annual emission per animal across the province was calculated as 0.35 kg CO_2e/hen.

The findings indicate that in districts with high-density production, increasing methane capture efficiency through the widespread adoption of biogas integration and covered storage systems, as well as adopting advanced manure management techniques such as scraper belts and closed units, could significantly reduce the regional greenhouse gas load (IPCC, 2019).

These data clearly demonstrate how the regional distribution of layer hen enterprises in Konya Province affects greenhouse gas emission quantities and serve as a guide for local administrations and producers in determining regional priorities for reducing the carbon footprint. They show that egg production activities in Konya are concentrated in specific geographical regions and that greenhouse gas emissions align with this density. For effective greenhouse gas reduction strategies, focusing on high-capacity districts is crucial for the efficient management of the carbon footprint.

Table 2. Emission values of CH_4 from manure management (kg/year), calculated CO_2 amounts (kg CO_2/year), and carbon footprint values (kg/hen*year) for layer hen enterprises in the 31 districts of Konya Province.

No	Districts	Number of Laying Hens (number)	Total annual CH_4 emission value (kg CH_4/Year)	Total annual CH_4 emission value for laying hens (kg CH_4/chicken*year)	CH_4 Emission (CO_2 equivalent) (kg CO_2/year)	Carbon footprint (kg/chicken* year)
1	Ahırlı	500	6,50	0,013	175,6	0,3512
2	Akören	3.900	50,73	0,013	1369,68	0,3512
3	Akşehir	165.025	2146,55	0,013	57956,75	0,3512
4	Altınekin	354.133	4606,35	0,013	124371,44	0,3512
5	Beyşehir	28.750	373,96	0,013	10096,99	0,3512
6	Bozkır	3198	41,60	0,013	1123,14	0,3512
7	Cihanbeyli	14.000	182,10	0,013	4916,8	0,3512
8	Çeltik	4.850	63,09	0,013	1703,32	0,3512
9	Çumra	521.000	6776,86	0,013	182975,1	0,3512
10	Derbent	2.075	26,99	0,013	728,74	0,3512
11	Derebucak	2.200	28,62	0,013	772,64	0,3512
12	Doğanhisar	7.160	93,13	0,013	2514,59	0,3512
13	Emirgazi	5.250	68,29	0,013	1843,8	0,3512
14	Ereğli	157.180	2044,50	0,013	55201,58	0,3512
15	Güneysınır	125.665	1634,57	0,013	44133,52	0,3512
16	Hadim	3.000	39,02	0,013	1053,6	0,3512
17	Halkapınar	1.877	24,41	0,013	659,2	0,3512
18	Hüyük	8.280	107,70	0,013	2907,93	0,3512
19	Ilgın	29.143	379,07	0,013	10235,02	0,3512
20	Kadınhanı	10.650	138,53	0,013	3740,28	0,3512
21	Karapınar	17.780	231,27	0,013	6244,33	0,3512
22	Karatay	1.705.560	22184,90	0,013	598992,33	0,3512
23	Kulu	1.315.890	17116,31	0,013	462140,3	0,3512
24	Meram	1.536.500	19985,87	0,013	539618,49	0,3512
25	Sarayönü	508.600	6615,56	0,013	178620,22	0,3512
26	Selçuklu	685.804	8920,53	0,013	240854,23	0,3512
27	Seydişehir	19.780	257,29	0,013	6946,73	0,3512
28	Taşkent	459	5,97	0,013	161,2	0,3512
29	Tuzlukçu	2.567	33,39	0,013	901,53	0,3512
30	Yalıhüyük	1.470	19,12	0,013	516,26	0,3512
31	Yunak	11.200	145,68	0,013	3933,44	0,3512
TOPLAM	KONYA	7.253.446	94348,47	0,013	2547408,78	0,3512

Tier 1a: N_2O Emissions from Manure Management

Direct N_2O Emissions

Using 2024 layer hen data from TÜİK (Turkish Statistical Institute) for the 31 districts of Konya Province, direct N_2O emissions from manure management were calculated with the Tier 1a method, assuming production in high-productivity cage systems and using data for "Poultry manure with litter." The analysis of direct N_2O emissions across 31 districts in Konya Province calculated an annual emission of 1,234.43 kg N_2O from operations housing 7,253,446 layer hens. Using the IPCC's 100-year global warming potential coefficient (GWP_{100} = 273 kg CO_2e/kg N_2O), this was converted to a total carbon equivalent of 337,000.18 kg CO_2e/year (IPCC, 2019). This result shows that although direct N_2O emissions from animal manure management occur in lower volumes compared to other greenhouse gases like methane, they represent a significant share in terms of carbon equivalent due to their high GWP value. The

district-based emission distribution is concentrated in Karatay (79,241.51 kg CO_2e; 23.5%), Meram (71,386.87 kg CO_2e; 21.2%), and Kulu (61,137.17 kg CO_2e; 18.1%). These three central districts alone account for approximately 62.8% of the total emissions, while Sarayönü (7.0%) and Selçuklu (9.5%) are also among the top five emission sources, contributing to 79.3% of the total. The individual shares of the remaining districts generally remain below 1%, indicating that the carbon load from N_2O is limited in small-capacity enterprises Table 3. The annual CO_2 equivalent per hen from direct N_2O was calculated to be approximately 0.046 kg CO_2e/hen*year. This low value highlights that direct N_2O emissions per animal unit are relatively small, but the total amount can increase rapidly with the scale of production. Therefore, promoting advanced manure management techniques such as covered storage or daily scraper systems, especially in high-density production centers like Karatay, Meram, and Kulu, could significantly reduce direct N_2O emissions. In conclusion, direct N_2O emissions from manure in Konya Province are directly related to the number of animals, the manure management system, and enterprise capacity. These data provide guidance for developing regional greenhouse gas reduction strategies, particularly in improving nitrogen management and manure application techniques in districts with large-scale production.

Table 3. Emission values of direct N_2O from manure management (kg/year), calculated CO_2 amounts (kg CO_2/year), and carbon footprint values (kg/hen*year) for layer hen enterprises in the 31 districts of Konya Province.

No	Districts	Number of Laying Hens (number)	Total annual N_2O_{direct} emission value (kg N_2O_{direct} /year)	Total annual N_2O_{direct} emission value for laying hens (kg N_2O_{direct} / chicken * year)	Total annual N_2O_{direct} emission value for laying hens (kg N_2O_{direct} / chicken * year)	N_2O_{direct} Emission (CO_2 equivalent) (kg CO_2/year)	Carbon footprint (kg/chicken*year)
1	Ahırlı	500	0,09	0,00018	0,18	23,23	0,0465
2	Akören	3.900	0,66	0,00017	0,17	181,2	0,0465
3	Akşehir	165.025	28,08	0,00017	0,17	7667,18	0,0465
4	Altınekin	354.133	60,27	0,00017	0,17	16453,27	0,0465
5	Beyşehir	28.750	4,89	0,00017	0,17	1335,75	0,0465
6	Bozkır	3198	0,54	0,00017	0,17	148,58	0,0465
7	Cihanbeyli	14.000	2,38	0,00017	0,17	650,45	0,0465
8	Çeltik	4.850	0,83	0,00017	0,17	225,33	0,0465
9	Çumra	521.000	88,67	0,00017	0,17	24206,02	0,0465
10	Derbent	2.075	0,35	0,00017	0,17	96,41	0,0465
11	Derebucak	2.200	0,37	0,00017	0,17	102,21	0,0465
12	Doğanhisar	7.160	1,22	0,00017	0,17	332,66	0,0465
13	Emirgazi	5.250	0,89	0,00017	0,17	243,92	0,0465
14	Ereğli	157.180	26,75	0,00017	0,17	7302,69	0,0465
15	Güneysınır	125.665	21,39	0,00017	0,17	5838,48	0,0465
16	Hadim	3.000	0,51	0,00017	0,17	139,38	0,0465
17	Halkapınar	1.877	0,32	0,00017	0,17	87,21	0,0465
18	Hüyük	8.280	1,41	0,00017	0,17	384,69	0,0465
19	Ilgın	29.143	4,96	0,00017	0,17	1354	0,0465
20	Kadınhanı	10.650	1,81	0,00017	0,17	494,81	0,0465
21	Karapınar	17.780	3,03	0,00017	0,17	826,07	0,0465
22	Karatay	1.705.560	290,26	0,00017	0,17	79241,51	0,0465
23	Kulu	1.315.890	223,95	0,00017	0,17	61137,17	0,0465
24	Meram	1.536.500	261,49	0,00017	0,17	71386,87	0,0465
25	Sarayönü	508.600	86,56	0,00017	0,17	23629,91	0,0465
26	Selçuklu	685.804	116,71	0,00017	0,17	31862,93	0,0465
27	Seydişehir	19.780	3,37	0,00017	0,17	918,99	0,0465
28	Taşkent	459	0,08	0,00017	0,17	21,33	0,0465
29	Tuzlukçu	2.567	0,44	0,00017	0,17	119,26	0,0465
30	Yalıhüyük	1.470	0,25	0,00017	0,17	68,3	0,0465
31	Yunak	11.200	1,91	0,00017	0,17	520,36	0,0465
	KONYA	7.253.446	1234,43	0,00017	0,17	337000,18	0,0465

Indirect N_2O Emissions from Manure Management

Indirect nitrous oxide (N_2O) emissions from manure management systems, specifically N_2O from volatilization, and their carbon dioxide equivalent (CO_2e) effects were analyzed for layer hen enterprises in Konya's 31 districts based on 2024 data (Tablo 4). The analysis for the 31 districts in Konya Province revealed annual emissions of 5,925.28 kg N_2O from volatilization, resulting in a carbon equivalent of 1,617,600.86 kg CO_2e/year, calculated using the IPCC GWP_{100} factor of 273 kg CO_2e/kg N_2O (IPCC, 2019). This shows that indirect N_2O constitutes a significant share of the total carbon equivalent from manure management, indicating that nitrogen losses through volatilization are a critical factor. The emission distribution is concentrated in Karatay (380,359.26 kg CO_2e; 23.5%), Meram (342,656.95 kg CO_2e; 21.2%), and Kulu (293,458.42 kg CO_2e; 18.1%). These three high-density production regions alone account for approximately 62.8% of the total indirect N_2O carbon equivalent. The average indirect N_2O carbon footprint per hen was calculated to be approximately 0.22 kg CO_2e/hen*year. For N_2O emissions from leaching, the fraction lost by leaching (Frac_leach) was determined to be zero based on IPCC 2019 guidelines, as the nitrogen is lost in the form of NH_3 and NO_x gases through volatilization. Therefore, the calculation for indirect N_2O emissions from leaching was not performed.

Table 4. Emission values of N_2O from volatilization from manure management (kg/year), calculated CO_2 amounts (kg CO_2/year), and carbon footprint values (kg/hen*year) for layer hen enterprises in the 31 districts of Konya Province.

No	Districts	Number of Laying Hens (number)	Total annual $N_2O_{volatilization}$ release value (kg $N_2O_{volatilization}$ / year)	Total annual $N_2O_{volatilization}$ emission value for laying hens (kg $N_2O_{volatilization}$ /chicken*year)	Total annual $N_2O_{volatilization}$ emission value for laying hens (kg $N_2O_{volatilization}$ /1000 chickens*year)	$N_2O_{volatilization}$ Emission (CO_2 equivalent) (kg CO_2/year)	Carbon footprint (kg/chicken*year)
1	Ahırlı	500	0,41	0,00082	0,82	111,51	0,22
2	Akören	3.900	3,19	0,00082	0,82	869,74	0,22
3	Akşehir	165.025	134,81	0,00082	0,82	36802,45	0,22
4	Altınekin	354.133	289,29	0,00082	0,82	78975,68	0,22
5	Beyşehir	28.750	23,49	0,00082	0,82	6411,58	0,22
6	Bozkır	3198	2,61	0,00082	0,82	713,19	0,22
7	Cihanbeyli	14.000	11,44	0,00082	0,82	3122,16	0,22
8	Çeltik	4.850	3,96	0,00082	0,82	1081,61	0,22
9	Çumra	521.000	425,6	0,00082	0,82	116188,92	0,22
10	Derbent	2.075	1,7	0,00082	0,82	462,75	0,22
11	Derebucak	2.200	1,8	0,00082	0,82	490,62	0,22
12	Doğanhisar	7.160	5,85	0,00082	0,82	1596,76	0,22
13	Emirgazi	5.250	4,29	0,00082	0,82	1170,81	0,22
14	Ereğli	157.180	128,4	0,00082	0,82	35052,93	0,22
15	Güneysınır	125.665	102,65	0,00082	0,82	28024,72	0,22
16	Hadim	3.000	2,45	0,00082	0,82	669,03	0,22
17	Halkapınar	1.877	1,53	0,00082	0,82	418,59	0,22
18	Hüyük	8.280	6,76	0,00082	0,82	1846,53	0,22
19	Ilgın	29.143	23,81	0,00082	0,82	6499,22	0,22
20	Kadınhanı	10.650	8,7	0,00082	0,82	2375,07	0,22
21	Karapınar	17.780	14,52	0,00082	0,82	3965,14	0,22
22	Karatay	1.705.560	1393,26	0,00082	0,82	380359,26	0,22
23	Kulu	1.315.890	1074,94	0,00082	0,82	293458,42	0,22
24	Meram	1.536.500	1255,15	0,00082	0,82	342656,95	0,22
25	Sarayönü	508.600	415,47	0,00082	0,82	113423,58	0,22
26	Selçuklu	685.804	560,23	0,00082	0,82	152942,08	0,22
27	Seydişehir	19.780	16,16	0,00082	0,82	4411,16	0,22
28	Taşkent	459	0,37	0,00081	0,81	102,36	0,22
29	Tuzlukçu	2.567	2,1	0,00082	0,82	572,47	0,22
30	Yalıhüyük	1.470	1,2	0,00082	0,82	327,83	0,22
31	Yunak	11.200	9,15	0,00082	0,82	2497,73	0,22
	KONYA	7.253.446	5925,28	0,00082	0,82	1617600,86	0,22

Total Emissions and Comparative Discussion

When the total greenhouse gas emissions from layer hen enterprises in Konya in 2024 are examined, the highest contribution comes from methane (CH_4) gas, as shown in Figure 2. Approximately 94,348 kg of CH_4 was emitted from these operations annually. Additionally, 1,234 kg of direct N_2O and 5,925 kg of N_2O from volatilization were calculated from manure management. Thus, the total greenhouse gas emission from layer hen farming in Konya reached approximately 101,508 kg/year. These results highlight the dominant effect of methane gas, while also showing that nitrous oxide emissions have a non-negligible environmental impact.

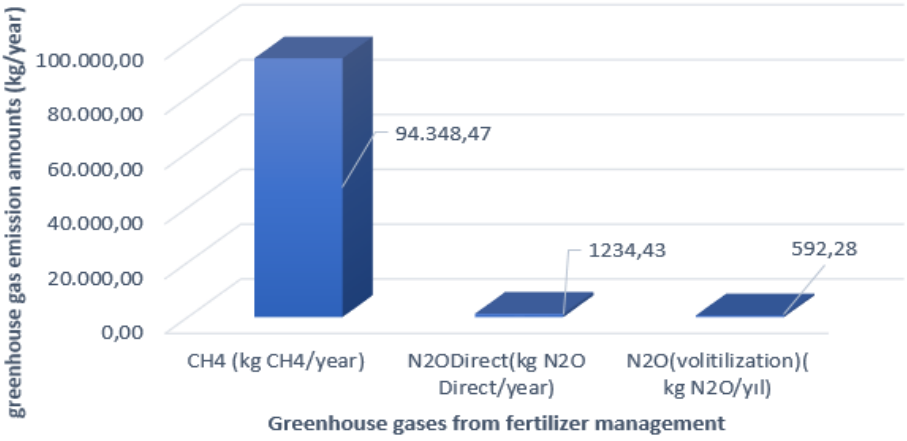

Figure 2. Emission values of CH_4, N_2O_{direct} and $N_2O_{volatilization}$ gases originating from manure management of laying hen farms for 31 districts of Konya Province in 2024 (kg/year)

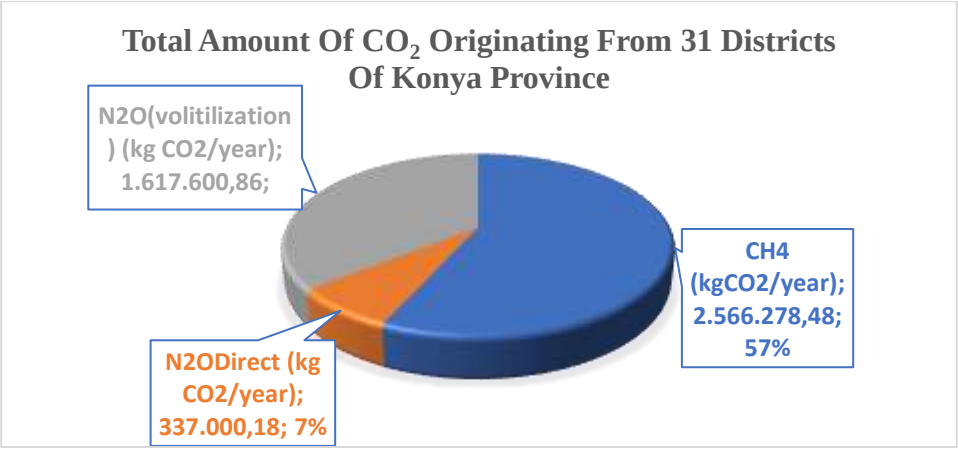

Figure 3. CO_2 amounts resulting from the release of CH_4 N_2O_{direct} and $N_2O_{volatilization}$ gases in laying hen farms for 31 districts of Konya Province in 2024, (kg).

Fabbri et al. (2007), monitoring annual NH_3, CH_4, and N_2O emissions in Italian farms with a capacity of about 60,000 hens, showed that the methane load was lower in belt systems. The high methane share in Konya confirms the necessity of appropriate manure management technologies (biogas, covered storage). Compared to the value of 1.6 kg CO_2e/kg egg calculated by Taylor et al. (2014) for mixed farms, the annual average of 0.62 kg CO_2e/hen in Konya indicates the effects of a similar or slightly higher intensity system.

Dunkley et al. (2015) reported total GHG emissions in the range of 917–1,757.8 tons CO_2e/year for four different operations, and Pishgar-Komleh et al. (2017) reported a value of 19.13 tons

CO_2e per 1000 broilers in Iran, which is consistent in magnitude with the 4,520 tons CO_2e calculated for 7.25 million hens in Konya. Fabbri et al. (2007) and other studies (Ahmet, 2019; Yaylı, 2019) provide context, with Konya's high absolute emissions highlighting the differences arising from the scale of the system. Compared to Yaylı's (2019) findings of 2.2–5.1 kg CO_2e/functional unit in broiler operations, this study emphasizes the potential for Konya's poultry sector to reduce its emission intensity by improving manure management technologies.

Recommendations

In conclusion, the calculations based on the cage system model in Konya's layer hen enterprises show that emission levels reach significant magnitudes, especially in districts with large-capacity operations. Parameters such as intensive production density, manure management practices, climatic conditions, and shelter ventilation are key factors explaining the differences in greenhouse gas emissions between districts. Emissions are closely related not only to animal numbers but also to the manner of manure management, litter use, system type (closed-open), storage duration, and local climatic conditions. Promoting biogas systems, converting manure storage to closed systems, and encouraging alternative management techniques like composting in high-emission districts will be effective in reducing the total greenhouse gas load. Developing sustainable manure management policies tailored to local conditions for Konya's layer hen enterprises will significantly contribute to reducing environmental impact.

Overall, it is understood that CH_4 emissions from the layer hen population in Konya are high in quantity, while N_2O emissions also contribute significantly, particularly through volatilization mechanisms. This situation reveals the importance of manure management and emission reduction strategies in the region's poultry activities and demonstrates that both direct and indirect greenhouse gas emissions must be controlled with an integrated approach.

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FAZ AÇISININ BESLENME DURUMU DEĞERLENDİRMESİNDEKİ YERİ

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ÖZET

Beslenme durumu değerlendirmesi, bireylerin sağlığının korunması, hastalıkların önlenmesi ve tedavi sürecinin etkin yönetimi açısından kritik bir süreçtir. Bu değerlendirme; antropometrik ölçümler, biyokimyasal göstergeler, klinik bulgular ve diyet öyküsünü kapsayan bütüncül bir yaklaşımla yapılmaktadır. Son yıllarda vücut kompozisyonunun ayrıntılı olarak belirlenmesine olanak sağlayan BİA, pratik, noninvaziv ve düşük maliyetli oluşu nedeniyle beslenme biliminde yaygın olarak kullanılmaktadır. Bu derlemenin amacı, beslenme durumunun değerlendirilmesinde kullanılan biyolojik empedans analizi (BİA) ve özellikle faz açısı (phase angle, PhA) parametresinin klinik ve sağlıklı popülasyonlarda kullanımını, belirleyicilerini ve prognostik değerini incelemektir. BİA ile hesaplanan faz açısı (PhA), hücre zarının kapasitif özelliklerini ve vücut sıvılarının dağılımını yansıtan, direnç (resistance) ve reaktans (reactance) değerlerinden türetilmiş bir parametredir. PhA, hücresel bütünlük ve vücut hücre kütlesinin dolaylı bir göstergesi olarak kabul edilmektedir. Düşük faz açısı değerleri genellikle hücre bütünlüğünün bozulduğunu, inflamasyon, malnütrisyon veya kronik hastalıkların varlığını işaret ederken; yüksek faz açısı değerleri sağlıklı hücresel yapı ve optimal beslenme durumuyla ilişkilendirilmiştir. Güncel literatür, PhA'nın yalnızca sağlıklı bireylerde değil; kanser, kronik böbrek hastalığı, HIV enfeksiyonu, yaşlılık ve yoğun bakımda izlenen hastalar gibi klinik popülasyonlarda da önemli bir prognostik biyobelirteç olduğunu ortaya koymaktadır. Düşük PhA, mortalite ve morbidite riskinin artışı ile, yüksek PhA ise daha iyi prognoz ve yaşam kalitesi ile ilişkilendirilmiştir. PhA'nın yorumlanmasında yaş, cinsiyet, etnik köken ve mevcut sağlık durumu gibi faktörler etkili olup, farklı popülasyonlar için standardizasyon ihtiyacı bulunmaktadır. Sonuç olarak, faz açısı beslenme durumunun objektif ve hassas bir göstergesi olarak hem araştırmalarda hem de klinik pratikte giderek önem kazanmaktadır. Ancak rutin klinik kullanımı için referans değerlerin netleştirilmesi, farklı popülasyonlar için kesme noktalarının belirlenmesi ve ölçüm koşullarında standardizasyonun sağlanması gerekmektedir.

Anahtar Kelimeler: Antropometrik ölçümler, Beslenme, Faz açısı

THE ROLE OF PHASE ANGLE IN NUTRITIONAL STATUS ASSESSMENT

ABSTRACT

Nutritional status assessment is a critical process for protecting individual health, preventing disease, and effectively managing treatment process. This assessment is conducted with a holistic approach encompassing anthropometric measurements, biochemical indicators, clinical findings, and dietary history. In recent years, BIA, which allows for detailed determination of body composition, has been widely used in nutritional sciences due to its practical, noninvasive, and low-cost nature. The aim of this review is to examine the use, determinants, and prognostic value of biological impedance analysis (BIA), and particularly phase angle (PhA) parameter, used in assessment of nutritional status in clinical and healthy populations. The phase angle (PhA) calculated by BIA is a parameter derived from resistance and reactance values, reflecting capacitive properties of the cell membrane and the distribution of body fluids. PhA is considered an indirect indicator of cellular integrity and body cell mass. While low phase angle values generally indicate impaired cell integrity, presence of inflammation, malnutrition, or chronic diseases; High phase angle values have been associated with healthy cellular structure and optimal nutritional status. Current literature demonstrates that PhA is an important prognostic biomarker not only in healthy individuals but also in clinical populations such as cancer, chronic kidney disease, HIV infection, aging, and patients in intensive care. Low PhA has been associated with an increased risk of mortality and morbidity, while high PhA has been associated with a better prognosis and quality of life. Factors such as age, gender, ethnicity, and current health status influence interpretation of PhA, necessitating standardization for different populations. Consequently, phase angle is gaining increasing importance as an objective and sensitive indicator of nutritional status in both research and clinical practice. However, for routine clinical use, reference values need to be clarified, cutoff points for different populations, and standardization of measurement conditions is necessary.

Keywords: Anthropometric measurements, Nutrition, Phase angle

Giriş

Beslenme durumu değerlendirmesi, bireylerin sağlığının korunması, hastalıkların önlenmesi ve tedavi sürecinin etkin bir şekilde yönetilmesi açısından kritik bir öneme sahiptir. Bu değerlendirme; antropometrik ölçümler, biyokimyasal parametreler, klinik bulgular ve diyet öyküsünü içeren çok boyutlu bir yaklaşımla gerçekleştirilir. Son yıllarda ise vücut kompozisyonunun daha ayrıntılı analizine olanak tanıyan biyolojik empedans analizi (BIA) yöntemleri, beslenme değerlendirmelerinde daha sık kullanılmaya başlanmıştır. BIA yöntemiyle elde edilen faz açısı (phase angle) parametresi, hücresel bütünlük ve vücut hücre kütlesi hakkında dolaylı bilgiler sağlayarak, beslenme durumunun objektif ve hassas bir göstergesi olma potansiyeli taşımaktadır (Unterberger et al., 2023). Faz açısı, hücre zarının kapasitif özelliklerini ve vücut içindeki sıvı dağılımını yansıtan, direnç (resistance) ve reaktans (reactance) değerlerinden hesaplanan bir parametredir. Düşük faz açısı değerleri, genellikle hücresel bütünlüğün bozulduğunu, inflamasyon veya malnütrisyon gibi durumların varlığını işaret ederken; yüksek faz açısı değerleri iyi hücresel bütünlük ve optimal beslenme durumu ile ilişkilendirilmiştir. Bu nedenle faz açısı hem sağlıklı bireylerde hem de hastalıklara sahip popülasyonlarda beslenme durumu takibinde önemli bir biyobelirteç olarak kabul edilmektedir (Rosa et al., 2025). Yapılan güncel çalışmalar, faz açısının özellikle kanser, kronik böbrek hastalığı, HIV, yaşlılık ve yoğun bakım gibi klinik durumlarda prognoz göstergesi olabileceğini ortaya koymakta ve bu parametrenin rutin beslenme değerlendirme süreçlerine entegrasyonunun faydalarını vurgulamaktadır. Ancak faz açısının klinik yorumlaması, bireyin yaşı, cinsiyeti ve hastalık durumuna göre farklılık gösterebileceğinden, standardizasyon ihtiyacı da dikkate alınmalıdır (Dolan et al., 2020; Rosa et al., 2025).

Beslenme Durumunun Değerlendirilmesi

Beslenme durumunu değerlendirirken, tek bir ideal testin bulunmadığını bilmek önemlidir. Bu nedenle, bilgiler sistemli bir şekilde toplanmalı ve elde edilen tüm veriler doğrultusunda genel bir değerlendirme yapılmalıdır. Amerikan Parenteral ve Enteral Beslenme Derneği (ASPEN) rehberlerine göre, kapsamlı bir beslenme değerlendirmesi; ayrıntılı tıbbi öykü ve fizik muayeneyi, antropometrik ölçümleri, tanısal testleri ve diyet analizlerini içermelidir (Mueller ve ark.,2011).

Antropometrik Ölçümler

Bireylerin beslenme durumları; zayıf, normal ya da kilolu olup olmadıklarının belirlenmesi yoluyla da değerlendirilebilmektedir. Bu amaçla, farklı değerlendirme yöntemleri geliştirilmiştir (Aslan ve ark, 2003). Antropometri, insan vücudunun ölçümüne yönelik bir bilim dalı olarak tanımlanır. Boy uzunluğu, bireyin ayakta dururken sahip olduğu yüksekliği ifade etmek için kullanılır. Vücut kompozisyonunun belirlenebilmesi için bireyin vücut ağırlığının ölçülmesi gereklidir. Bu ölçümde ağırlık birimi olarak kilogram (kg) kullanılmaktadır (Beam ve Adams, 2013). Antropometrik ölçümler, vücuttaki protein ve yağ depolarını yansıttıkları için beslenme durumunun belirlenmesinde önemli bir yer tutar (Baysal ve ark, 2013).

Antropometrik değerlendirmelerde en sık başvurulan yöntemler şu şekilde sınıflandırılabilir:

- Vücut ağırlığı ve boy uzunluğu ölçümleri
- Beden Kütle İndeksi (BKİ) hesaplaması
- Bel ve kalça çevresi ölçümleri ile bel/kalça oranı
- Vücut bileşimi analizleri (Baysal ve ark, 2013).

Vücut Bileşimi

Boy, ağırlık, beden kütle indeksi (BKİ), bel-kalça çevresi ve bel/kalça oranı gibi ölçümler beslenme durumunun değerlendirilmesinde önemli göstergelerdir. Ancak bu ölçümler, vücuttaki kas ve yağ gibi bileşenleri birbirinden ayırt edemezler. Bu nedenle, bu temel ölçümlere ek olarak vücut bileşimi analizlerinin de yapılması gereklidir. Vücut bileşimi analizi; toplam vücut ağırlığının, yağ kütlesi ve yağsız vücut kütlesi şeklinde iki ana bileşene ayrılmasını sağlar. Daha detaylı analizlerde ise bu bileşenlere ek olarak toplam vücut suyu miktarı da değerlendirilebilmektedir (Kayan, 2012). Vücut kompozisyonunu ölçmeye yönelik çalışmalar, 1940'lı yıllarda A.R. Behnke'nin öncülüğünde başlamıştır (Sarıtaş ve ark, 2011). Vücut kompozisyonu; yaş, cinsiyet, kas kütlesi, fiziksel aktivite düzeyi, mevcut hastalıklar ve bireyin beslenme durumu gibi çeşitli faktörlere bağlı olarak değişiklik gösterebilir (Tepe 2014). Vücut kompozisyonunu belirlemek amacıyla yöntem seçilirken; ekipman ve personel maliyeti, ölçüm süresi, radyasyona maruz kalma durumu ile elde edilen verilerin doğruluk düzeyi gibi faktörler göz önünde bulundurulmalıdır (Andreoli vd 2016). Vücut kompozisyonu ölçüm yöntemleri; doğrudan (direkt), dolaylı (indirekt) ve çift dolaylı (çift indirekt) yöntemler olmak üzere üç grupta sınıflandırılmaktadır. Direkt yöntemler, vücudun kimyasal yapısını doğrudan analiz ederek ölçüm yapan tekniklerdir. İndirekt yöntemler ise, nekropsi çalışmalarından elde edilen verilerin çeşitli formüller aracılığıyla değerlendirilmesine dayanır. Çift indirekt yöntemler ise, bir indirekt yöntemin sağladığı veriler ile belirli bir parametre arasındaki istatistiksel ilişkiler temel alınarak geliştirilmiştir. Bu yöntemler arasında antropometrik ölçümler, biyoelektrik impedans analizi ve deri kıvrım kalınlığı ölçümleri yer almaktadır (Victor, 2012). Ancak, vücut kompozisyonunu belirlemede kullanılan referans yöntemler genellikle zaman alıcı, uygulaması güç ve yüksek maliyetlidir. Bu nedenle, daha pratik ve erişilebilir bir alternatif olarak biyoelektrik impedans analizi (BİA) yaygın şekilde tercih edilmektedir (Canbolat, 2018).

Tablo 1. Vücut Kompozisyonu Değerlendirmede Kullanılan Yöntemlerin Kısıtlılıkları ve Avantajları (Tepe, 2014)

Yöntem	Güvenirlik	Masraf	Radyasyon	Zaman	Hasta Uyumu
Biyoelektrik İmpedans	+	+		+++	+++
Antropometri	+	+++		++	+
DEXA	++	-	-	++	++
BT	++	--	--	++	++
MRI	++	--		++	+
Nötron Aktivasyon	+++	--	--	++	++
40 K Analizi	++	-	-	++	++
Dansitometri	++			++	+/-
+++:Mükemmel	++:Çok iyi	+:İyi	+/-:Kötü Değil	-:Kötü	--:Çok Kötü

Biyoelektrik Empedans Analizi (BİA)

Klinik uygulamalarda, beslenme alışkanlıklarının değerlendirilmesinin yanı sıra vücut kompozisyonunun analiz edilmesi de büyük önem taşımaktadır. Bu amaçla, genellikle noninvaziv, uygulanması kolay ve düşük maliyetli bir yöntem olan biyoelektrik impedans analizi (BİA) tercih edilmektedir (Barrea ve ark., 2021). Biyoelektrik impedans analizi (BİA), ellere ve ayaklara yerleştirilen dört elektrot aracılığıyla, faz duyarlılığı bulunan bir impedans cihazı kullanılarak gerçekleştirilir. Bu yöntemde, vücuda ağrısız, sabit ve düşük seviyeli 50 kHz frekansında, 800 µA'lik bir elektrik akımı uygulanır. Farklı vücut dokularının bu akıma gösterdiği direnç (empedans) farklılıklarına dayanarak vücut bileşenleri hakkında bilgi elde edilir (Lukaski, Kyle ve Kondrup, 2017).

Biyoelektrik impedans analizi (BİA) cihazı aracılığıyla aşağıdaki parametreler belirlenebilmektedir:

1. Vücut yağ yüzdesi ve yağ kütlesi,
2. Yağsız doku oranı ve kütlesi,
3. Toplam vücut ağırlığının bileşenlerine göre dağılımı (yüzde olarak),
4. Vücut sıvı miktarı (toplam vücut suyu),
5. Tahmini bazal metabolizma hızı,
6. Tahmini ortalama günlük enerji gereksinimi,
7. Beden kütle indeksi (BKİ),
8. Elektrik akımının geçişine karşı oluşan direnç (impedans) (Özçetin ve ark., 2017).

Ayrıca BİA, bireysel sıvı dağılımını ve tüm vücuttaki hücre zarı bütünlüğünü değerlendirerek, hücre ölümü ve hücresel hasarla ilişkili inflamatuar biyobelirteçleri dolaylı olarak tanımlamada kullanılan basit ve bilimsel olarak doğrulanmış bir yöntemdir (Lukaski ve ark., 2017)

BİA Ölçümü Öncesi Dikkat Edilmesi Gereken Durumlar

1. Ortam Sıcaklığı: Ölçümün yapıldığı oda serin (~14°C) olmamalıdır. Düşük ortam sıcaklığı, deri ısısında azalmaya ve buna bağlı olarak toplam vücut direncinde artış ile yağsız vücut kütlesinde azalmaya neden olabilir.
2. Açlık Durumu: Ölçüm öncesinde en az 4 saatlik bir açlık süresi gereklidir.
3. Fiziksel Aktivite: Ölçümden 24–48 saat önce ağır fiziksel egzersiz yapılmamalıdır.
4. Alkol Tüketimi: Testten en az 24 saat önce alkol alınmamalıdır.
5. Sıvı Tüketimi: Ölçüm öncesinde aşırı miktarda su içilmemelidir.
6. İdrar Boşaltımı: Testten yaklaşık 30 dakika önce mesane boşaltılmalıdır.
7. Kafein Tüketimi: Ölçümden en az dört saat önce çay, kahve, kola gibi kafein içeren içeceklerin tüketiminden kaçınılmalıdır.
8. Menstruasyon Dönemi: Kadın bireylerde adet dönemi sırasında ölçüm yapılmamalıdır, çünkü bu dönemde sıvı dengesinde değişiklik olabilir.
9. Metal Takılar: Ölçüm sırasında kişinin üzerinde metal takı, kemer, saat gibi iletken materyaller bulunmamalıdır.
10. Kalp Pili: Ölçüm yapılacak bireyde kalp pili bulunmamalıdır (Nalçacıoğlu,2014).

BİA'nın Bileşenleri

Biyoelektrik impedans analizinde (BİA), alternatif akıma karşı gösterilen direnç olan empedans (Z), vücuttaki su ve elektrolit içeriği ile bunların dağılımına bağlı olarak vücut kompozisyonunu yansıtmaktadır (Kyle ve ark., 2004). Biyoelektrik impedans analizi, vücut kompozisyonunu belirlerken elektriksel reaktans ve rezistans değerlerinden yararlanmaktadır (Bosy-Westphal ve ark., 2006). Empedans (Z), rezistans (R) ve reaktans (Xc) olmak üzere iki temel bileşenden oluşmaktadır. Rezistans, elektrik akımının geçişine karşı hücre içi ve dışı sıvıların gösterdiği toplam direnci ifade eder; bu direnç özellikle hücre dışı sıvı miktarına bağlıdır. Reaktans ise, elektrik yükünü alternatif biçimde depolayan ve akımın geçişini geciktirerek bu yükün serbest kalmasını sağlayan hücre membranlarının kapasitif özelliklerinden kaynaklanır. Bu durum, hücre membranlarının oluşturduğu direnç olarak tanımlanabilir ve büyük ölçüde vücut hücre kütlesine dayanır (Kyle ve ark., 2004). Rezistans (R), vücuttaki su içeriğiyle ters orantılıdır. Bu nedenle, vücutta ödem gibi durumlarda ya da aşırı sıvı alımının ardından, su miktarındaki artışa bağlı olarak R değeri düşer. Buna karşılık, dehidrasyon gibi su kaybı yaşandığında ise R değeri yükselir. Başka bir deyişle, vücutta sıvı fazlalığı olduğunda elektrik iletkenliği artar ve direnç azalır; sıvı azaldığında ise iletkenlik düşer ve direnç yükselir. Bu bağlamda, yüksek rezistans değeri bireyin dehidrate olduğunu, düşük rezistans değeri ise ödem varlığına işaret etmektedir (Harrisville, 2009). Reaktans (Xc), vücut hücre kütlesiyle doğru orantılıdır. Bu nedenle, birey sağlıklı ve yeterli beslendiğinde hücre zarlarının bütünlüğü korunur ve hücrelerin elektriksel yükü tutma kapasitesi artar; bu durum reaktans değerinin yüksek olmasına yol açar. Buna karşılık, hücresel yapıların bozulduğu, yetersiz beslenme veya ileri düzey kilo kaybı gibi durumlarda hücre sayısı ve zar bütünlüğü azaldığı için Xc değeri düşer. Reaktansın yüksek olması, genellikle bireyin beslenme durumunun iyi olduğunu; düşük olması ise yetersiz beslenmeyi ve potansiyel hücresel hasarı işaret eder. Xc değerinin zamanla sabit kalması ise, kişinin metabolik durumunun ve beslenme dengesinin istikrarlı olduğunu gösterebilir (Harrisville, 2009). Klinik uygulamalarda en iyi tanımlanmış impedans parametresi faz açısıdır. Çeşitli hastalıklarda klinik sonuçları ve mortaliteyi yüksek oranda öngördüğü gösterildiğinden, bu parametre son yıllarda giderek daha fazla önem kazanmıştır. Empedans matematiksel olarak $Z^2=R^2 + Xc^2$ denklemi ile tanımlanır (Norman ve ark., 2012). Biyoelektrik impedans analizi, vücut kompozisyonunu reaktans ve rezistans ölçümleri aracılığıyla değerlendirir. Rezistans ile reaktans arasındaki ilişki sonucu ortaya çıkan faz açısı, hücre kompozisyonu, sıvı volümü ve hücre membran potansiyeline bağlı olarak değişmekte olup; yaş, cinsiyet gibi bireysel faktörlerden de etkilenmektedir (Bosy-Westphal ve ark., 2006). Düşük faz açısı, genellikle düşük reaktans ve yüksek rezistans ile birlikte görülür ve bu durum hücre zarı bütünlüğünde azalmayı göstermektedir. Buna karşın, yüksek faz açısı değerleri, yüksek reaktans ve düşük rezistans ile karakterize olup, daha fazla sağlam hücre zarı varlığını işaret eder (Selberg & Selberg, 2002).

Faz Açısı

Faz açısı (PhA), biyoelektrik impedans analizinde önemli bir parametre olup, hücresel sağlığın göstergesi olarak kabul edilmektedir. Ayrıca, yapılan çalışmalar faz açısının kötü prognoz, yetersiz beslenme, fonksiyon kaybı ve mortalite ile ilişkili olduğunu ortaya koymaktadır. Bunun yanı sıra, faz açısının oksidatif stresle de bağlantılı olabileceği düşünülmektedir (da Silva, Gonzalez, Cereda ve Prado, 2021). Bunun yanı sıra, faz açısı çeşitli hastalıklarda morbidite ve mortalite göstergesi olarak da kullanılmaktadır (Norman ve ark., 2010; Stobäus ve ark., 2012).

Faz açısı (PhA), reaktansın elektrik direncine oranı olarak tanımlanır ve hücre zarı bütünlüğü ile vücut hücre kütlesine bağlıdır. Ayrıca, PhA değerleri ile vücut hücre kütlesi arasında anlamlı

bir korelasyon bulunmaktadır (Kumar ve ark., 2012). Faz açısının kullanımı, vücut sıvılarındaki değişikliklerin olduğu ya da vücut ağırlığının ölçülemediği hastalarda bile uygulanabilir olması nedeniyle önemli bir avantaj sağlamaktadır (Motta ve ark., 2015). Faz açısı, rezistans (R) ve reaktans (Xc) olmak üzere iki bileşenden oluşur. Faz açısı, Xc ile R arasındaki oranın arktanjantı alınarak hesaplanır ve aşağıdaki formülle ifade edilir (da Silva, Gonzalez, Cereda ve Prado, 2021).

Faz Açısı (PhA)(°) = arctan(Reaktans/Rezistans)* (180/π)

Çeşitli çalışmalarda, HIV enfeksiyonu, karaciğer hastalıkları, kanser, yoğun bakımda tedavi gören hastalar, cerrahi ve kemoterapi uygulanan bireyler ile yaşlılarda düşük faz açısının kötü prognozun önemli bir göstergesi olduğu rapor edilmiştir (Garlini ve ark., 2019).

Faz Açısının Değerlendirilmesi

Sağlıklı bireylerde faz açısı genellikle 6° ile 7° arasında değişirken, atletlerde bu değer 8,5°'ye kadar çıkabilmektedir. Düşük faz açısı (<5°) ise hücresel bütünlüğün kaybını işaret eder. Faz açısının hücresel bütünlükle güçlü bir ilişkiye sahip olması, onu empedansa kıyasla beslenme durumunun daha hassas bir göstergesi haline getirmektedir (Marra ve ark., 2019).

Faz Açısını Etkileyen Etmenler

Faz açısı, cinsiyet, yaş, fiziksel aktivite, beslenme durumu ve hastalık gibi çeşitli faktörlerden etkilenmektedir (Canbolat, 2018).Sağlıklı bireylerde faz açısının (PhA) başlıca belirleyicileri cinsiyet, yaş ve beden kütle indeksi (BKİ) olarak tanımlanmaktadır (Kyle ve ark., 2012; Norman ve ark., 2012). Ayrıca, sağlıklı ve hastalıklı durumlar arasında PhA değerlerinde anlamlı farklılıklar gözlenmektedir (Kyle ve ark., 2012). Malnütrisyon da dahil olmak üzere çeşitli hastalık durumlarında PhA genellikle normalin altında seyretmekte olup, kronik hastalıklarda mortalitenin prognostik göstergesi olarak kullanımı önerilmektedir (Norman ve ark., 2010).

Cinsiyet ve yaş

Geniş kapsamlı bir çalışmada, 18-94 yaş aralığında 1967 sağlıklı yetişkinin faz açıları incelenmiş ve ortalama faz açısı 6,93±1,15° olarak belirlenmiştir. Araştırma, faz açısı (PhA) değerlerinin yaş ve cinsiyete göre değişimini ortaya koymuştur. Bulgulara göre, erkeklerin faz açısı değerleri kadınlara göre daha yüksek bulunmuştur. Ayrıca, yaş ilerledikçe faz açısı değerlerinde azalma eğilimi gözlemlenmiştir. Örneğin, erkeklerde genç yaş grubunda (18-20 yaş) ortalama faz açısı 7,90° iken, yaşlı grup (≥70 yaş) için bu değer 6,19° olarak saptanmıştır. Kadınlarda ise bu değerler sırasıyla 7,04° ve 5,64° olarak rapor edilmiştir (Barbosa-Silva ve ark.,2005). Yine bu konuda yapılan geniş kapsamlı bir çalışmada, 1013 sağlıklı yetişkin bireyin faz açıları incelenmiş ve erkeklerde ortalama faz açısı 6,1±0,8°, kadınlarda ise 5,6±0,7° olarak saptanmıştır (Barrea ve ark.,2017). 2015 ile 2020 yılları arasındaki veriler kullanılarak gerçekleştirilen ve 1877 kişinin değerlendirildiği bir araştırmada, 983 obez birey (BKİ ≥30 kg/m²) ile 894 obez olmayan birey incelenmiştir. Erkek obez grubunda ortalama Faz Açısı (PhA) 6.80° iken, kontrol grubundaki erkeklerde bu değer 6.86° olarak saptanmıştır. Kadınlarda ise obez bireylerin PhA ortalaması 6.21°, obez olmayanların ise 6.16°'dir. Genel olarak erkeklerdeki PhA değerleri, kadınlara kıyasla belirgin biçimde daha yüksektir (Di Vincenzo ve ark.,2023). İlgili çalışmalar incelendiğinde, erkek bireylerin faz açısı değerlerinin kadınlara kıyasla; genç bireylerin ise yaşlı bireylere oranla daha yüksek olduğu gözlemlenmektedir. Bu durum, erkeklerin ve genç yaştaki bireylerin kadınlara ve yaşlı bireylere göre daha fazla kas kütlesine ve daha düşük yağ kütlesine sahip olmalarıyla açıklanabilir (Canbolat,2018).

Beslenme Durumu

Beslenme durumu ile faz açısı arasındaki ilişki çeşitli araştırmalarda ele alınmıştır. Yapılan çalışmalar, faz açısı ile malnütrisyon değerlendirme araçlarından Subjektif Global Değerlendirme (SGA) ve Mini Nütrisyonel Değerlendirme (MNA) arasında negatif bir korelasyon olduğunu ortaya koymuştur. Uygun beslenme uygulamaları ve malnütrisyonun tedavisiyle faz açısında artış gözlemlenebilmektedir (Ayyıldız ve ark.,2016). BKİ ile faz açısı arasındaki ilişki değerlendirildiğinde, vücutta artan vücut kütle indeksiyle birlikte yağ ve kas hücrelerinin sayısındaki artışa bağlı olarak faz açısının da yükseldiği ifade edilmektedir. Ancak bu pozitif ilişkinin genellikle BKİ'si 30 kg/m²'nin altında olan bireylerde görüldüğü; BKİ'si 40 kg/m²'yi aşan obez bireylerde ise bu ilişkinin ters yönde seyrettiği rapor edilmiştir (Bosy-Westphal ve ark.,2006). 2014–2022 yılları arasında gerçekleştirilen ve 1079 hasta ile 86 sağlıklı bireyin değerlendirildiği bir çalışmada, malnütre, obez ve sağlıklı bireyler arasındaki faz açısı (PhA) değerleri karşılaştırılmıştır. Bulgulara göre, obezite grubunda PhA 5.98°, malnütrisyon grubunda 4.79° ve sağlıklı bireylerde ise 6.08° olarak saptanmıştır. Ayrıca, faz açısının yaşla negatif yönde, vücut kütle indeksi (BKİ) ile ise pozitif yönde ilişkili olduğu belirlenmiştir (Saavedra Vásquez ve ark.,2024). Sonuç olarak, faz açısının beslenme durumu ve buna bağlı olarak vücut ağırlığından etkilendiği açıkça görülmektedir. Ancak, faz açısına ilişkin standart referans aralıklarının belirlenmemiş olması, beslenme durumunun değerlendirilmesinde kesin ve net bir yargıya varılmasını zorlaştırmaktadır (Canbolat,2018).

Fiziksel Aktivite Düzeyi

Faz açısının, toplam vücut protein miktarı, kas kütlesi ve el kavrama gücü ile ilişkili olduğu bilinmektedir (Ayyıldız ve ark.,2016). Sağlıklı bireylerde faz açısı genellikle 5° ile 7° arasında değişmekte olup, bu değer atletik bireylerde 9.5°'ye kadar çıkabilmektedir (Norman ve ark., 2012). 2021 yılında 66 katılımcı ile gerçekleştirilen bir çalışmada, spor yapan bireylerle spor yapmayanlar arasındaki faz açısı (PhA) farkları incelenmiştir. Erkek sporcularda ortalama PhA değeri 6.85 ± 0.50 iken, sedanter erkek bireylerde bu değer 6.29 ± 0.67 olarak ölçülmüştür. Kadınlarda ise sporcuların ortalama PhA değeri 5.61 ± 0.44, sedanter bireylerde ise 5.47 ± 0.58 olarak bulunmuştur. Elde edilen sonuçlara göre, sporcuların faz açısı değerleri sedanter bireylere kıyasla anlamlı düzeyde daha yüksek çıkmıştır. Ayrıca, özellikle erkek katılımcılarda PhA'nın fiziksel aktivite düzeyiyle ilişkili olduğu belirlenmiştir (Šeper ve ark., 2021). Fiziksel aktivitenin faz açısı üzerindeki olumlu etkisinin olası mekanizması şu şekilde açıklanmaktadır: Uzun süreli egzersiz sonucunda glikojen depolarındaki artış, hücre içi su (ICW) dengesinin sağlanmasına katkı sağlar. Bu durum, glikojenin her gramının yaklaşık 3 gram su ile birlikte depolanması özelliğinden kaynaklanmaktadır. ICW dengesinin korunması, kas protein sentezinin artmasına ve protein yıkımının azalmasına yol açar. Bu süreçte, kas dokusundaki artışa bağlı olarak reaktans yükselirken, artan ICW oranı nedeniyle rezistans azalır ve bu da faz açısında yükselmeye neden olur (Souza ve ark.,2017).

Faz Açısı ve Hastalıklar

Faz açısı, hücre zarının elektriksel bütünlüğünün bir göstergesi olduğundan, enflamasyon, enfeksiyon gibi membran yapısını bozan patolojik durumlardan doğrudan etkilenmektedir (Zhang ve ark., 2014). 2022 yılında yayımlanan bir çalışmada, 2014-2016 yılları arasında 427 erişkin HIV pozitif birey değerlendirilmiştir. Araştırmada, faz açısı (PhA) kesim değerleri HIV pozitif erkeklerde 5.45°, kadınlarda ise 4.95° olarak belirlenmiştir. Bu değerlerin altında kalan bireylerin, GLIM kriterlerine göre malnütrisyon riski taşıdığı tespit edilmiştir (Osuna-Padilla ve ark., 2022). 2022 yılında yayımlanan bir çalışmada, kolorektal kanser hastalarının faz açısı (PhA) değerlendirilmiştir. Toplamda 160 hasta incelenmiş ve ortalama PhA değeri yaklaşık 5.3° olarak bulunmuştur. Ayrıca, faz açısının her 1° artışında mortalite riskinin %21 oranında

azaldığı belirlenmiştir (Han ve ark., 2022). Schmidt ve arkadaşlarının yürüttüğü araştırmada, 158 meme kanseri hastasında faz açısı (PhA) değerleri değerlendirilmiştir. Çalışmanın sonuçlarına göre, katılımcıların ortalama PhA değeri yaklaşık 5.5° ± 0.8° olarak belirlenmiştir (Schmidt ve ark., 2023). Lim ve arkadaşları tarafından 2021 yılında yapılan bir araştırmada, 152 hemodiyaliz hastası değerlendirilmiştir. Erkek hastalarda ortalama faz açısı 4.62° ± 0.82 olarak ölçülmüştür. Kadın hastalarda ise bu değer biraz daha düşük olup, 3.92° ± 0.88 olarak bulunmuştur. Sonuçlar, erkek hemodiyaliz hastalarının kadınlara kıyasla daha yüksek faz açısı değerlerine sahip olduğunu göstermektedir (Lim ve ark., 2021). Chen ve arkadaşları tarafından gerçekleştirilen bir çalışmada, 101 periton diyalizi hastası değerlendirilmiştir. Araştırmada hastaların faz açısı (PhA) değerleri ölçülmüştür. Elde edilen bulgulara göre, ortalama faz açısı 5.4° olarak belirlenmiştir (Chen ve ark.,2022). Koçak ve arkadaşları tarafından 2024 yılında yayımlanan bir araştırmada, 60 yaş ve üzeri toplam 135 geriatrik hasta incelenmiştir. Çalışmada katılımcıların faz açısı (PhA) değerleri ölçülmüş ve ortalama faz açısı 5.4° olarak tespit edilmiştir (Koçak ve ark.,20224). Saueressig ve arkadaşları tarafından yürütülen bir çalışmada, 97 siroz hastasının faz açısı (PhA) değerleri incelenmiştir. Araştırma sonuçlarına göre, tüm katılımcıların ortalama faz açısı 5.4° ± 1.0° olarak belirlenmiştir. Ayrıca yapılan detaylı analizler neticesinde, sirozlu hastalar için malnütrisyon riskini belirlemede kullanılabilecek faz açısı kesim değeri ≤ 5.52° olarak saptanmıştır (Sauerressig ve ark.,2020). İncelenen çalışmalar göz önüne alındığında, hastalık durumunun faz açısını negatif yönde etkilediği söylenebilir (Canbolat,2018). Çalışmalarda faz açısı kesim değerlerinin farklılık gösterdiği görülse de, Norman ve arkadaşlarının belirlediği bazı hastalıklara ait kesim noktaları Tablo 2'de sunulmuştur. Bu kesim noktalarının altında kalan faz açısı değerleri, hastalık riskinin artmasıyla ilişkilendirilmektedir (Norman ve ark.;2012).

Tablo 2. Bazı hastalıklara ait faz açısı kesişim değerleri

Hastalık	**Faz Açısı**
HIV	5,3°-5,6°
Akciğer Kanseri	4,5°
Kolerektal Kanser	5,57°
Pankreas Kanseri	5,08°
Meme Kanseri	5,6°
Hemodiyaliz	3,0°-6,0°
Periton Diyalizi	6,0°
Karaciğer Sirozu	5,4°
Amyotrophic Lateral Skleroz	2,5°
Geriatrik Hastalar	3,5°
Sistemik Skleroz	3,9°
* (HIV):İnsan İmmün Yetmezlik Sendromu	

Sonuç ve Öneriler

BİA ölçümlerinde sıkça tercih edilen parametrelerden biri faz açısıdır. Faz açısının en büyük avantajlarından biri, vücut sıvılarındaki değişikliklerin olduğu ya da vücut ağırlığının

ölçülemediği hastalarda bile rahatlıkla kullanılabilmesidir. Faz açısı, diğer BİA parametrelerine kıyasla daha yeni bir kavramdır ve hücresel sağlık ile hidrasyon durumunu yansıtabilme özelliği taşır. Malnütrisyonun tespitinde yenilikçi bir yöntem olarak öne çıkmasının yanı sıra, henüz standart bir referans değerinin bulunmaması bu alana olan ilgiyi artırmıştır. Faz açısı ile ilgili güncel akademik çalışma sayısı uluslararası literatürde olduğu gibi ülkemizde de giderek artmaktadır. Ancak çalışmalar genel olarak hastalıklar üzerine yapılmakta olup gebe, çocuk gibi farklı popülasyonlar üzerine yapılan çalışma sayısı oldukça azdır. Ayrıca faz açısı alanında birçok çalışma yapılmış olsa da henüz farklı popülasyonlardaki bireylerde referans faz açısı değerleri belirlenememiştir. Buna sebep olarak faz açısının yaş, cinsiyet, hastalık gibi birçok faktörden etkilenmesi gösterilebilir. Sonuç olarak faz açısı hücresel sağlığı değerlendirmek adına kullanılabilecek kolay ulaşılabilir bir parametre olsa da klinik olarak kullanılıp yaygınlaşması için daha geniş örneklem büyüklüğüne sahip, farklı popülasyonları da ele alan daha fazla çalışmaya ihtiyaç vardır.

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İRRİTABL BAĞIRSAK SENDROMU VE BESLENME: TANIDAN TEDAVİYE KANITA DAYALI YAKLAŞIMLAR

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ÖZET

İrritabl Bağırsak Sendromu (İBS), dünya genelinde milyonlarca bireyi etkileyen ve en sık karşılaşılan fonksiyonel gastrointestinal bozukluklardan biri olup, toplum sağlığı açısından önemli bir sorun teşkil etmektedir. Kronik ve tekrarlayıcı karın ağrısı, şişkinlik, dışkılama alışkanlıklarında değişiklik, kabızlık, ishal veya bu semptomların dönüşümlü olarak görülmesi ile karakterize olan bu sendrom, bireylerin yaşam kalitesini belirgin şekilde azaltmakta, iş gücü kaybına ve sağlık hizmetleri kullanımında artışa yol açarak sağlık sistemine ciddi ekonomik yük getirmektedir. İBS'nin etiyolojisi karmaşık ve multifaktöriyel olup, tek bir nedene indirgenememektedir. Bu derlemenin amacı, İBS'nin tanı kriterleri, sınıflandırılması ve patofizyolojik mekanizmalarına ilişkin güncel bilgileri literatür ışığında ele almak; hastalığın ortaya çıkışında rol oynayan beslenme ve yaşam tarzı faktörlerini tartışmak; özellikle son dönemde öne çıkan düşük fermente olabilen oligosakkaritler, disakkaritler, monosakkaritler ve polioller (FODMAP) diyetinin etkinliğini, uygulanabilirliğini ve sınırlılıklarını değerlendirmektir. Bu kapsamda, klinisyenler ve diyetisyenler için İBS semptomlarının yönetiminde kullanılabilecek kanıta dayalı yaklaşımlar ortaya konulmaya çalışılmıştır. Son yıllarda düşük FODMAP diyeti, İBS semptomlarının kontrolünde en çok ilgi gören beslenme stratejilerinden biri haline gelmiştir. Diyet, FODMAP sınırlanmasına dayanmakta ve bu bileşenlerin bağırsakta hızla fermente olarak gaz üretimine, osmotik yük artışına ve buna bağlı olarak şişkinlik, karın ağrısı ve dışkılama düzensizliklerine yol açtığı bilinmektedir. Randomize kontrollü klinik çalışmaların sonuçları, düşük FODMAP diyetinin İBS'li bireylerin %50–75'inde semptomlarda anlamlı düzeyde iyileşme sağladığını göstermektedir. Bununla birlikte, uzun süreli ve katı uygulamaların bağırsak mikrobiyotasında çeşitlilik kaybına yol açabileceği, besin ögesi yetersizlikleri riski oluşturabileceği ve diyete uyumun zamanla zorlaşabileceği

bildirilmektedir. Bu nedenle, düşük FODMAP diyetinin mutlaka kişiselleştirilmiş bir beslenme planı çerçevesinde ve uzman bir diyetisyen rehberliğinde uygulanması önerilmektedir. Sonuç olarak, İBS multifaktöriyel yapısı nedeniyle bireyselleştirilmiş tanı ve tedavi yaklaşımlarını gerektiren bir hastalıktır. Özellikle düşük FODMAP diyeti, kanıta dayalı bulgularla desteklenen etkili bir yöntem olmakla birlikte, sınırlılıkları da göz önünde bulundurulmalı ve uzun vadeli yönetimde dengeleyici stratejiler uygulanmalıdır.

Anahtar Kelimeler: Beslenme, FODMAP Diyeti, İrritabl Bağırsak Sendromu

IRRITABLE BOWEL SYNDROME AND NUTRITION: EVIDENCE-BASED APPROACHES FROM DIAGNOSIS TO TREATMENT

ABSTRACT

Irritable Bowel Syndrome (IBS) is one of the most common functional gastrointestinal disorders, affecting millions of individuals worldwide and posing a significant public health problem. The purpose of this review is to review current information on the diagnostic criteria, classification, and pathophysiological mechanisms of IBS in light of the literature; to discuss the nutritional and lifestyle factors that play a role in the disease's development; and to evaluate the effectiveness, applicability, and limitations of the recently emerging low-fermentable oligosaccharides, disaccharides, monosaccharides, and polyols (FODMAP) diet. In this context, we aimed to present evidence-based approaches that can be used by clinicians and dietitians in the management of IBS symptoms. In recent years, the low-FODMAP diet has become one of the most popular nutritional strategies for managing IBS symptoms. The diet is based on restricting FODMAPs, and it is known that these compounds rapidly ferment in the intestine, leading to gas production, increased osmotic load, and consequent bloating, abdominal pain, and defecation irregularities. Results of randomized controlled clinical trials indicate that a low-FODMAP diet provides significant symptom relief in 50–75% of individuals with IBS. However, it has been reported that long-term and strict adherence may lead to a loss of diversity in the gut microbiota, pose a risk of nutrient deficiencies, and make adherence to the diet more difficult over time. Therefore, it is recommended that a low-FODMAP diet be implemented within the framework of a personalized nutrition plan and under the guidance of a registered dietitian. In conclusion, due to its multifactorial nature, IBS is a disease that requires individualized diagnostic and therapeutic approaches. While the low-FODMAP diet, in particular, is an effective method supported by evidence-based findings, its limitations should also be considered, and compensatory strategies should be implemented in long-term management.

Keywords: Nutrition, FODMAP Diet, Irritable Bowel Syndrome

Giriş

İrritabl Bağırsak Sendromu (İBS), küresel ölçekte en yaygın görülen fonksiyonel gastrointestinal bozukluklardan biridir. Bu sendromla yaşayan bireylerde, sağlıklı popülasyona kıyasla yaşam kalitesinin belirgin şekilde azaldığı bildirilmiştir. İBS'nin kronik yapısı, toplumda sık görülmesi ve sıklıkla eşlik eden diğer sağlık sorunları, hastalığın sağlık sistemine ve topluma olan ekonomik yükünü artırmaktadır. İBS'nin altında yatan biyolojik mekanizmalar hâlâ tam olarak aydınlatılamamış olup, mevcut tedavi yaklaşımlarını destekleyen bilimsel kanıtlar tutarsızlık göstermektedir. Bu belirsizlikler, özellikle beslenme temelli yaklaşımlara olan ilgiyi son yıllarda belirgin biçimde artırmıştır (Özyürek ve Pekcan, 2023). Hastaların önemli bir kısmı, yaşadıkları semptomları tükettikleri besinlerle ilişkilendirmekte olup, beslenme alışkanlıkları bu bireylerin günlük yaşamlarını etkileyen temel unsurlardan biri olarak öne çıkmaktadır. Fermente olabilen oligosakkaritler, disakkaritler, monosakkaritler ve polioller (FODMAP) bakımından sınırlı bir diyetin, diğer beslenme yaklaşımlarına kıyasla daha etkili sonuçlar verdiği gösterilmiştir. Bu nedenle, düşük FODMAP diyeti günümüzde birçok klinisyen tarafından İBS yönetiminde ilk tercih edilen beslenme stratejisi olarak değerlendirilmektedir (Bellini vd., 2020).

İrritabl bağırsak sendromu

İBS, bağırsak ile beyin arasındaki karmaşık iletişim sürecini içeren, uzun süreli bir sağlık sorunudur ve bağırsak-beyin etkileşimi bozuklukları (DGBI) arasında en yaygın olanlardan biridir (Bertin vd., 2024). Genel popülasyonda yaygınlığı, kullanılan tanı ölçütleri ve bölgesel farklılıklara göre %3,8 ile %12 arasında değişiklik göstermektedir. Türkiye'deki kesin yaygınlık oranı bilinmemekle birlikte bazı çalışmalarda İBS'nin toplumda %19 oranında görüldüğü ve kadınlarda daha yaygın olduğu bildirilmektedir (Özyürek ve Pekcan, 2023). İBS, dışkılama süreciyle bağlantılı olarak ya da bağırsak alışkanlıklarındaki değişimle birlikte görülen, tekrarlayan karın ağrısıyla karakterizedir. Bu duruma çoğunlukla karında şişkinlik veya gerginlik gibi belirtiler eşlik eder (Ooi vd., 2019). Güncel araştırmalar, mukozal dokularda özellikle mast hücreleri ve eozinofiller gibi bağışıklık hücrelerinin birikiminin, ağrıya yol açan kimyasalların salınımını tetiklediğini göstermektedir. Bu maddelerin duyusal sinirleri uyarması, viseral hassasiyetin artmasına ve rahatsız edici belirtilerin ortaya çıkmasına katkı sağlar. Bağışıklık sisteminin bu tür bir aktivasyonu, bağırsak bariyerinde oluşan bozulmalarla iç içe geçer; ayrıca bu süreçte bağırsak mikrobiyotasındaki değişiklikler, beslenme alışkanlıkları ve psikolojik stres gibi etkenler de rol oynar (Vanuytsel vd., 2023). İBS yaşamı doğrudan tehdit etmese de, bireylerin yaşam kalitesini ciddi biçimde düşürebilir; bu durum sağlık hizmetlerine başvuru sıklığında artışa ve iş gücü verimliliğinde azalmaya yol açabilir (Cassar vd., 2020). Bu semptomların ortaya çıkmasında diyetin önemli bir rol oynayabileceği düşünülmektedir. İBS tanısı almış hastaların yaklaşık %20 ila %65'i semptomlarının gıda tüketimiyle ilişkili olduğunu bildirmektedir. Son on yılda, özellikle fermente olabilen oligosakkaritler, disakkaritler, monosakkaritler ve polioller açısından düşük içerikli diyetlerin geliştirilmesiyle birlikte İBS'nin diyetle yönetimi konusunda ilgi belirgin şekilde artmıştır. Düşük FODMAP diyetinin uygulanması, yapısal olarak karmaşık bir süreçtir ve diyetin alanda eğitimli ve deneyimli bir diyetisyen tarafından yönlendirilmesi önerilmektedir (Mehtap vd., 2019).

İrritabl Bağırsak Sendromu Tanı Kriterleri

İBS tanısı için altın standart Roma IV kriterleridir (Baykut ve Baykan, 2024). İBS tanısında kullanılan Roma IV kriterlerine göre, tanı konulabilmesi için hastada son 3 ay içinde, haftada ortalama en az bir gün karın ağrısının tekrar etmesi ve bu ağrının üç özelliğin en az ikisiyle ilişkili olması gerekir. Bu özellikler: dışkılama ile bağlantılı olması, dışkılama sıklığında bir

değişiklik olması ve dışkının görünümünde bir değişiklik bulunmasıdır. Bu semptomların tanıdan en az 6 ay önce başlamış ve son 3 ay boyunca düzenli şekilde devam etmiş olması da gerekmektedir. Roma IV kriterlerine göre İBS, dışkılama alışkanlıklarının baskın özelliğine göre dört alt tipe ayrılmaktadır: Kabızlığın baskın olduğu tip (İBS-C), ishalin baskın olduğu tip (İBS-D), kabızlık ve ishal dönemlerinin dönüşümlü olduğu karışık tip (İBS-M) ve belirtilerin bu sınıflamalardan herhangi birine uymadığı, sınıflandırılamayan tip (İBS-U) (Ooi vd., 2019).

Her ne kadar belirlenmiş tanı kriterleri mevcut olsa da İBS tanısı, günlük klinik pratikte hala önemli bir zorluk oluşturmaktadır. Fiziksel belirti ya da laboratuvar bulgularının genellikle olmaması nedeniyle tanı çoğu zaman benzer belirtilere yol açan diğer hastalıkların dışlanması yoluyla konulmaktadır. Bu nedenle, tanı süreci çoğunlukla kapsamlı bir değerlendirme ve ayırıcı tanı gerektirir (Sobolewska vd., 2020). Semptomlara dayalı Roma IV kriterlerinin kullanımı ile semptomların değerlendirilmesi, bazı laboratuvar testleri, bazı popülasyonlarda çölyak hastalığının dışlanması, fiziki muayene (rektal muayene dahil) İBS tanısını koymak için genellikle yeterli olmaktadır (Lacy vd., 2023).

İrritabl Bağırsak Sendromunun Sınıflandırılması

İBS tanısında temel belirti, tekrarlayan karın ağrısının varlığıdır. Karın ağrısı olmadan İBS tanısı konulamaz. Bu ağrının, haftada ortalama en az bir gün olacak şekilde düzenli olarak ortaya çıkması gerekmektedir. İBS alt türlerinin belirlenmesinde (İBS-C, İBS-D, İBS-M ve İBS-U) dışkı formunun değerlendirilmesi önemlidir ve bu amaçla Bristol Dışkı Formu Ölçeği kullanılır. Dışkının şekli, hangi alt tipe girildiğinin belirlenmesinde temel unsurlardan biridir (Kingsley vd., 2020).

Bristol dışkı formu ölçeğinde yedi tür dışkı tanımlanmaktadır:

• Tip 1: Fındık gibi sert topaklar

• Tip 2: Sosis şeklinde fakat topaklı

• Tip 3: Sosis gibi ama yüzeyinde çatlaklar var

• Tip 4: Sosis veya yılan gibi, pürüzsüz ve yumuşak

• Tip 5: Keskin kenarlı yumuşak lekeler (kolayca geçer)

• Tip 6: Pürüzlü kenarları olan yumuşak parçalar

• Tip 7: Sulu, katı parça yok, tamamen sıvı

İBS alt tiplerinin doğru şekilde belirlenebilmesi için hastaların 14 gün boyunca bağırsak alışkanlıklarını kaydettikleri bir günlük tutmaları gerekmektedir. Bu süreçte dışkıların değerlendirilmesinde Bristol Dışkı Formu Ölçeği kullanılır. Bu ölçeğe göre, dışkı tipleri 1 ve 2 kabızlıkla, tip 6 ve 7 ise ishalle ilişkilendirilir ve anormal olarak kabul edilir. Tip 3 ve 4 dışkılar ise normal kabul edilir (Lacy ve Patel, 2017). Bristol ölçeği, hastaların dışkı formunu daha iyi tanımlayabilmesine olanak sağlar ve bu nedenle hem klinik uygulamalarda hem de araştırmalarda yaygın olarak tercih edilmektedir. İBS alt tiplerinin sınıflandırılmasında, dışkı formunun en az %25 oranında belirli bir tipe uyması dikkate alınır. Örneğin, dışkılamalarının %25'inden fazlası tip 1 veya 2 olan bireyler İBS-C olarak sınıflandırılırken; dışkılamalarının %25'inden fazlası tip 6 veya 7 olan bireyler İBS-D olarak değerlendirilir (Lacy ve Patel, 2017).

İrritabl Bağırsak Sendromu Etiyolojisi ve Patofizyolojisi

IBS, etiyolojisi bilinmemekle birlikte çok sayıda patofizyolojik mekanizma ile karakterize çok faktörlü bir hastalıktır. İBS; mikrobiyom değişiklikleri, visseral veya merkezi aşırı duyarlılık, beyin-bağırsak etkileşimlerinin değişmesi, anormal gastrointestinal hareketlilik, psikososyal

faktörler, genetik faktörler, bozulmuş safra asidi metabolizması ve besinlere aşırı duyarlılık dahil olmak üzere heterojen ve tam olarak anlaşılmamış bir patofizyolojiye sahiptir (Özyürek ve Pekcan, 2023).

İrritabl Bağırsak Sendromu ve Tedavi Yaklaşımları

İBS tedavisi genellikle baskın semptomlara dayanmaktadır kanıtlanmış net bir tedavi yoktur. Semptomlardan sorumlu olan patofizyolojik etkenin tedavisine yönelik bir yol izlenmektedir. Son 20 yılda çeşitli hedefli tedavilerin geliştirilmesine rağmen, çoğu ilaç sınırlı etkinlik göstermektedir ve plasebo yanıt oranları yüksektir (Bertin ve ark. 2024). Birçok hasta uzun süreler boyunca ilaç almaktan kaçındığından alternatif yaklaşımlar denemektedir (Özyürek ve Pekcan, 2023). İBS hastalarının %70'inden fazlası semptomlarının besinsel kaynaklı olduğunu belirtmektedir. Bu besinler, farklı fizyolojik mekanizmalar üzerinden etki göstererek karın ağrısı, şişkinlik, gaz ve bağırsak alışkanlıklarında değişiklik gibi belirtileri tetikleyebilir. Bu nedenle İBS'nin tedavisinde diyet müdahalelerine olan ilgi artmaktadır. Bu yüzden bireyler ilaçlara başvurmak yerine çeşitli diyetleri (glutensiz diyetler, düşük laktozlu diyetler, fruktozsuz diyetler ve IgG antikor testine dayalı eliminasyon diyetleri) tercih etmektedir ancak bu diyetlere ilişkin çalışmalardan elde edilen destekleyici veriler sınırlıdır (Bertin vd., 2024). FODMAP olarak adlandırılan fermente edilebilir kısa zincirli karbonhidratlar, bağırsaklarda ozmotik yük oluşturur ve bakteriyel fermantasyon süreciyle birlikte şişkinlik, gaz oluşumu ve visseral duyarlılığın artmasına neden olabilir. Yağ içeriği yüksek besinler, mide boşalmasını yavaşlatır ve kolesistokinin salınımını uyararak mide bulantısı ve hazımsızlık hissini artırabilir. Kafein ve alkol, mide asidi salgısını artırarak bağırsak bariyerinde bozulmalara yol açabilir ve böylece bağırsak geçirgenliğini artırabilir. Baharatlı gıdalar, özellikle TRPV1 adı verilen ağrı reseptörlerini uyararak karın ağrısının şiddetini artırabilir. Yapay tatlandırıcılar ise bağırsak mikrobiyotasında değişikliklere neden olarak ishal gibi sindirim problemlerine zemin hazırlayabilir. Histamin yönünden zengin gıdalar da mast hücrelerini aktive ederek inflamasyonu tetikleyebilir ve bu da İBS semptomlarının kötüleşmesine katkı sağlayabilir (Kasti vd., 2025). Klinik kılavuzlar, İBS yönetiminde ağırlıklı olarak iki temel beslenme yaklaşımına odaklanmaktadır. İlk basamak diyet tedavisi, İngiliz Diyetisyenler Derneği ile Ulusal Sağlık ve Bakım Mükemmelliği Enstitüsü (NICE) tarafından önerilen geleneksel İBS diyetidir. Bu yaklaşım; yaşam tarzı değişiklikleri, düzenli öğün tüketimi, fiziksel aktivitenin artırılması, yağ oranı yüksek besinlerin azaltılması, büyük porsiyonlardan kaçınılması, çözünmeyen lifin sınırlandırılması ve bazı yaygın besin tetikleyicilerinin diyetten çıkarılmasını içermektedir. Eğer bireyler bu standart önerilere ya da ilk basamak farmakolojik tedaviye yeterli yanıt vermezse, daha özel bir beslenme planı için diyetisyene yönlendirilebilirler. Bu durumda uygulanan başlıca alternatif yaklaşımlardan biri, fermente olabilen kısa zincirli karbonhidratların sınırlanmasına dayalı olan düşük FODMAP diyetidir (Colomier vd., 2022). FODMAP bileşenleri, bağırsakta zayıf emildiğinden suyun bağırsak lümenine çekilmesine neden olur ve kolona ulaştıklarında bağırsak bakterileri tarafından fermantasyona uğrayarak gaz üretir. Bu süreç bağırsak duvarında gerilmeye ve hareketlilik değişikliklerine yol açarak semptomların ortaya çıkmasına katkı sağlayabilir. Yapılan randomize kontrollü çalışmalar, düşük FODMAP diyetini uygulayan İBS'li bireylerin yaklaşık %50 ila %75'inde semptomlarda belirgin rahatlama sağlandığını göstermektedir (Halmos vd., 2014 ; De Roest vd., 2013). Ancak, bu durum aynı zamanda hastaların %25 ila %50'sinin bu yaklaşıma yanıt vermediğini ortaya koymaktadır. Bu nedenle, hangi bireylerin bu diyet tedavisinden fayda sağlayabileceğini önceden öngörebilmek, daha kişiselleştirilmiş ve etkili bir tedavi planı oluşturmak açısından büyük önem taşımaktadır (Bertin vd., 2024). İBS hastalarının belirli besin gruplarından kaçınmasına rağmen toplumdaki sağlıklı bireylerle kıyaslandığında günlük kalori, karbonhidrat, protein ve yağ alımı bakımından herhangi bir farka rastlanmamıştır.

Ancak çalışmalar düşük FODMAP'in uzun süre uygulanmasının demir, folat, magnezyum, kalsiyum, B ve C vitaminleri gibi temel besin maddelerinin yetersiz alımına neden olabileceğini göstermektedir (Bellini vd., 2020).

Fodmap diyet tedavisi

Avustralya'daki Monash Üniversitesi'nde 2005 yılında Dr. Sue Shepherd ve Prof. Peter Gibson başkanlığındaki araştırmacılar, FODMAP terimini ortaya attılar (Bertin vd., 2024). FODMAP'leri, özellikle İBS'li bireylerde gastrointestinal semptomları ortaya çıkarabilen belirli fermente edilebilir karbonhidratlar için bir kategorizasyon olarak kavramsallaştırdılar (Gibson vd., 2005). FODMAP, "Fermente Edilebilir Oligo-, Di- ve Mono-sakkaritler ve Polioller", yüksek derecede fermente olabilen ancak zayıf bir şekilde absorbe edilen kısa zincirli karbonhidratlar ve poliollerin heterojen dağılan bir grubudur (Catassi vd., 2017). FODMAP'ler çok çeşitli sebzelerde, meyvelerde, buğday ve tahıl gruplarında, süt ve süt ürünlerinde, baklagillerde ve tatlandırıcılarda yaygındır. Normal bir diyette toplam FODMAP alımı günlük 15 ila 30 gram arasında değişmektedir (Varney vd., 2017). Düşük FODMAP diyeti, İBS beslenme temelli tedavisinde yaygın olarak kullanılan ve bilimsel olarak desteklenen bir yaklaşımdır. Bu diyet iki temel yöntemle uygulanabilir: yukarıdan aşağıya ve aşağıdan yukarıya yaklaşım. Yukarıdan aşağıya yaklaşım, genellikle daha yaygın olarak tercih edilen ve daha fazla bilimsel kanıtla desteklenen bir yöntemdir. Bu yaklaşım üç aşamalı bir süreçten oluşur. İlk aşamada, FODMAP içeren tüm gıdalar kısa süreliğine diyetten tamamen çıkarılır. İkinci aşamada, bu besinler kontrollü bir şekilde ve tek tek yeniden diyete eklenerek bireysel tolere edilebilirlik değerlendirilir. Son aşamada ise, elde edilen tolere edilebilirlik verilerine göre kişiye özel ve sürdürülebilir bir beslenme düzeni oluşturulur. Aşağıdan yukarıya yaklaşım ise daha sınırlı ve hedefe yönelik bir stratejidir. Bu yöntemde başlangıçta sadece belirli FODMAP grupları diyetten çıkarılır. Eğer semptomlarda iyileşme sağlanmazsa, kısıtlamalar diğer FODMAP gruplarını da içerecek şekilde genişletilir. Her iki yöntem de İBS semptomlarının hafifletilmesinde etkili olabilir. Ancak mevcut araştırmalar, özellikle yukarıdan aşağıya yaklaşımın daha başarılı sonuçlar verdiğini göstermektedir. Bu nedenle, düşük FODMAP diyetinin uzman bir sağlık profesyoneli rehberliğinde uygulanması önerilmektedir (Singh vd., 2022). FODMAP'lerin bağırsak işlevini etkileyen üç temel özelliği olduğu düşünülmektedir. Bu özellikleri ince bağırsakta sınırlı düzeyde emilmeleri, küçük ve ozmotik olarak aktif moleküller olmaları, kalın bağırsakta hızlı bir şekilde bakteriyel fermantasyona uğramalarıdır (Bertin vd., 2024). Yetersiz emilim birden fazla mekanizmayla açıklanabilir. Örneğin, bazı bireylerde fırça kenarı enzimlerinden laktazın azalmış aktivitesi laktozun emilimini zorlaştırırken, fruktanlar ve galaktanlar için sindirici enzimlerin tamamen bulunmaması da bu maddelerin ince bağırsakta parçalanmadan kalın bağırsağa ulaşmasına neden olur. Ayrıca, polioller gibi bazı büyük moleküller, basit difüzyon yoluyla taşınamayacak kadar hacimlidir. Bunlara ek olarak, ince bağırsak epitelinde yer alan taşıyıcı proteinlerin yavaş çalışması ve düşük taşıma kapasitesine sahip olması da FODMAP emilimini sınırlandıran diğer etkenlerdendir. Özellikle fruktoz, GLUT taşıyıcı ailesine ait iki özel taşıyıcı protein yoluyla emilir. GLUT5 proteini yalnızca fruktoz taşımaya özelleşmişken, GLUT2 hem fruktoz hem de glikoz ile galaktoz taşınmasını sağlar. Fruktozun glikoz ile birlikte alınması, emilim etkinliğini artırabilir. Ancak, bu iki şeker arasında dengesizlik varsa, örneğin fruktoz alımı glikozdan fazlaysa, emilim bozulabilir ve fruktoz kalın bağırsağa ulaştığında burada mikrobiyal fermantasyona uğrar (Wilder vd., 2018). Sonuç olarak, FODMAP'lerin emilim kapasitesi; tüketilen miktar, bağırsak geçiş süresi, lümendeki glikoz düzeyi ve bireyin GLUT2 ve GLUT5 taşıyıcılarının etkinliği gibi çeşitli faktörlerden etkilenir. Bu bireysel farklılıklar, FODMAP' lere verilen yanıtların kişiden kişiye değişmesinin temelini oluşturur. Ozmotik etki, 1,4 beta galaktozid-fruktoz olarak da bilinen sentetik bir FODMAP olan laktuloz üzerinden

örneklendirilebilir. Galaktoz ve fruktozdan oluşan bu yapay disakkarit, vücut tarafından emilemez ve ince bağırsakta su miktarını artırarak bağırsak hareketlerini etkiler. Bu özelliği sayesinde yeterli miktarda alındığında müshil etkisi oluşturur. Bakteriyel fermantasyonun hızı ise karbonhidrat zincirinin uzunluğuna bağlıdır; oligosakkaritler ve basit şekerler, polisakkaritlere kıyasla daha hızlı fermente olur (Bertin vd., 2024).

Fermente Edilebilir Kısa Zincirli Karbonhidratlar

Sindirim için gerekli olan hidrolaz enzimlerinin eksikliği, düşük yoğunluğu ya da monosakkaritler söz konusu olduğunda ince bağırsaktan tam olarak emilememelerinden dolayı kolonda fermente olmaya uygun yapıdadırlar. Kısa zincirli fermente edilebilir karbonhidratlar bağırsakta hidrojen (H_2) ve metan (CH_4) gazlarının üretimini artırarak, visseral aşırı duyarlılığı olan bireylerde bağırsak içinde gerginlik ve buna bağlı ağrı hissine yol açabilir. Bu grupta öncelikle fruktoz, laktoz, fruktanlar, galaktooligosakkaritler ve polioller yer almaktadır.

Fruktanlar

Fruktanlar, inülin, oligofruktoz ve fruktooligosakkaritlerden (FOS) oluşan, fruktozdan meydana gelen kısa zincirli karbonhidratlardır. İnsan sindirim sistemi, bu bileşiklerdeki β-fruktozil-fruktoz bağlarını parçalayacak enzimlere sahip değildir. Bu nedenle, fruktanlar ince bağırsakta sindirilmeden kalın bağırsağa ulaşır. En yaygın fruktan kaynakları arasında buğday ve soğan gibi gıdalar yer alır. Bu besinlerde fruktan miktarı düşük olsa da, genellikle büyük porsiyonlarla tüketilirler. Fruktanların ayrıca prebiyotik özellik taşıdığı, yani bağırsak mikrobiyotasını olumlu yönde etkileyebildiği bilinmektedir (Staucher vd., 2014).

Galaktooligosakkaritler

Galaktooligosakkaritler (GOS), sindirimi için gerekli olan α-galaktozidaz enziminin insan vücudunda bulunmaması nedeniyle ince bağırsakta sindirilemez ve kolona ulaşarak burada fermente olur. Bu özellikleri sayesinde prebiyotik etkiler gösterirler. GOS'un temel kaynakları arasında baklagiller, bazı tahıllar, kuruyemişler, tohumlar ve anne sütü yer alır (Biesiekierski vd., 2011).

Laktoz

Laktoz, süt ve süt ürünlerinde bulunan bir disakkarittir ve sindirimi için laktaz enzimine ihtiyaç duyar. Laktaz enziminin etkinliği yaşla birlikte azalabilir; bu durum özellikle Akdeniz ve Asya kökenli bireylerde, ayrıca inflamatuvar bağırsak hastalıkları gibi durumlarda daha belirgin hale gelir. İBS hastalarında laktoz malabsorbsiyonu %18–82 oranında görülür ama bu oran genel nüfustan daha yüksek değildir (Yang vd., 2013).Birçok birey, diyet laktozunu sindirmek için yeterli laktaz üretimine sahiptir ve bu nedenle düşük FODMAP diyetinin bir parçası olarak laktozu kısıtlamaya ihtiyaç duymazlar.

Fruktoz

Fruktoz, FODMAP grubundaki en küçük molekül yapısına sahip olan monosakkarittir. Elma, armut, karpuz, mango gibi meyveler; bezelye gibi bazı sebzeler; bal ve yüksek fruktozlu mısır şurubu gibi ürünlerde bulunur. Fruktoz bağırsakta yavaş ve sınırlı şekilde emilir. Bu emilim süreci sırasında osmotik etkisi nedeniyle bağırsak lümenine su çeker ve bu da şişkinlik, karın ağrısı ve hatta ishal gibi semptomlara yol açabilir. Son araştırmalar fruktozun yalnızca emilemeyen kısmının değil, emilen kısmının da semptomlara katkıda bulunabileceğini göstermiştir. Bu nedenle, fruktozun emilim kapasitesinden çok, toplam alımı önem taşır (Murray vd., 2014).

Polioller

Polioller, şeker alkolleri olarak da bilinen ve özellikle sorbitol ile mannitol gibi bileşenleri içeren bir FODMAP grubudur. Elma, armut, erik, şeftali gibi meyveler; karnabahar, mantar ve bezelye gibi sebzeler doğal poliol kaynaklarıdır. Ayrıca ksilitol, izomalt gibi polioller birçok şekersiz sakız ve şekerlemede tatlandırıcı olarak kullanılır. Polioller ince bağırsakta yavaş emilir ve emilim düzeyine bakılmaksızın suyu bağırsağa çekerek osmotik etki oluşturur. Bu durum, şişkinlik, gaz ve dışkılama değişikliklerine neden olabilir. Bu nedenle polioller, İBS semptomlarının değerlendirilmesinde dikkate alınması gereken önemli bir faktördür (Yao vd., 2014).

Düşük Fodmap Diyeti Uygulaması

FODMAP açısından zengin besinlerin bireyde semptomlara yol açıp açmadığını belirlemek amacıyla bu tür gıdalar geçici olarak diyetten çıkarılır veya sınırlandırılır. Bu diyet yaklaşımı iki temel aşamadan oluşur. Birinci aşama, genellikle 4 ila 8 hafta sürer. Bu dönemde, yüksek FODMAP içeren tüm besinler diyetten uzaklaştırılır. Bu süreçte, bir öğünde alınan FODMAP miktarı 0,5 gramı, günlük toplamda ise 3 gramı geçmemelidir. İkinci aşama, yeniden tanıtım sürecidir. Bu aşamada, ilk olarak laktoz içeren süt ve süt ürünleri haftada üç gün olacak şekilde diyete yeniden dahil edilir. Eğer bu gıdanın eklenmesi semptomlarda belirgin bir kötüleşmeye neden olursa, ilgili gıda tekrar diyetten çıkarılır. Ancak herhangi bir semptom artışı gözlenmezse, bireyin bu besini daha yüksek miktarda tüketmesine izin verilir. Bu aşamadan sonra diğer FODMAP gruplarının yeniden tanıtımı planlı bir şekilde sürdürülür. Her yeni gıda eklemesinden önce genellikle 2-3 günlük bir dinlenme (arınma) süreci uygulanır. Bu sayede semptom takibi daha net bir şekilde yapılabilir (Zannetti vd., 2018). Son on yılda, Monash Üniversitesi Gastroenteroloji Bölümü, meyve, sebze, tahıl, tahıl ürünleri, süt ürünleri, et ürünleri, içecekler ve çeşniler gibi farklı gıda kategorilerinde FODMAP içeriğini belirlemek amacıyla kapsamlı araştırmalar gerçekleştirmiştir. Bu çalışmalar sonucunda, sürekli güncellenen ve birçok dilde kullanılabilen Monash Üniversitesi düşük FODMAP diyet uygulaması oluşturulmuştur. Bu uygulama sayesinde, doğru FODMAP verilerine dünya genelinde erişim kolaylaşmış ve diyetin etkin şekilde uygulanması desteklenmiştir (Muir vd., 2009). Günlük terapötik hedef olarak önerilen maksimum FODMAP alımı 12 gramdır. Genel nüfusun ortalama FODMAP tüketimi bu sınırın üstünde olup, yaklaşık 19,86 gram/gün olarak tahmin edilmiştir (Zanzer vd., 2024). Düşük FODMAP diyetinin eliminasyon fazında, çoğu katılımcı bu sınırın altında, yani günde 12 gramdan az FODMAP tüketmiştir. Özellikle fruktan alımı sıkı fazda 2,2 gramın altına düşmüş ve bu azalma uzun vadede de korunmuştur. Ancak düşük FODMAP için ideal bir eşik miktar henüz netleşmemiştir (Rej vd., 2021).

İBS'DE DÜŞÜK FODMAP DİYETİNİN ETKİNLİĞİ

İBS hastalarının büyük bir kısmı, besin tüketimi ile semptomlar arasında bir bağlantı olduğunu ifade etmektedir. Bu nedenle, yemek sonrası rahatsızlık yaşayan bazı hastalar diyetlerini ciddi şekilde kısıtlamakta ve belirli gıdalardan tamamen kaçınmaktadır. Bu durumu yaşayan hasta grubunda, semptomların daha yoğun seyrettiği, yaşam kalitesinin düştüğü, enerji alımının azaldığı ve çeşitli besin ögelerinin alımında eksiklikler yaşandığı gözlemlenmektedir (Melchior vd., 2021). Yemekle ilişkili semptomların bu kadar ön plana çıkması, İBS'de beslenmeye dayalı tedavi yaklaşımlarına olan ilgiyi artırmıştır. İBS için günümüzde önerilen başlıca diyet yaklaşımları üç grupta toplanmaktadır: geleneksel diyet önerileri (TDA), düşük FODMAP diyeti (LFD) ve glutensiz diyet(GFD). Geleneksel diyet yaklaşımı; düzenli öğün tüketimini, yağlı ve baharatlı yiyeceklerin, kafeinli, alkollü ve gazlı içeceklerin ve lif alımının sınırlandırılmasını önermektedir. Düşük FODMAP diyeti ise, porsiyon başına alınan toplam FODMAP miktarını azaltmayı hedefler. Düşük FODMAP diyetinin, İBS semptomlarını %70'e

varan oranlarda hafifletebildiği gösterilmiştir (Halmos vd., 2014). Prospektif, randomize bir çalışma İBS-D'li hastalarda düşük FODMAP diyeti ve geleneksel diyet tedavisinin etkilerini gözlemlemek için yürütülen bir çalışmada karın ağrısı sıklığı, karın şişkinliği ve bağırsak alışkanlıklarından memnuniyetsizlik TDA'ya kıyasla 4. haftada önemli iyileşme göstermiştir. Dışkı sıklığı ve formu önemli bir iyileşme gösteririken, IBS ilaç kullanımında azalma meydana gelmiştir (Goyal vd. 2021). Çalışmalarda FODMAP'lerin bağırsak epitel bariyerini geçirgen hale getirebileceği, bağışıklık sistemini aktive edebileceği ve düşük dereceli inflamasyonu tetikleyebileceği öne sürülmektedir. Bu etkilerin, İBS'nin ortaya çıkışında önemli bir rol oynayabileceği düşünülmektedir (Goyal vd. 2021) İBS hastalarında kişisel özelliklerin (bağırsak florası, psikolojik durum, yeme alışkanlıkları) hangi diyet tedavisine, hangi belirti (karın ağrısı, şişkinlik, kabızlık, ishal) için daha iyi yanıt verdiğini inceleyen bir araştırmada orta ve şiddetli IBS tanısı almış düşük FODMAP diyeti uygula ve geleneksel IBS diyeti uygulanmıştır. Her iki grupta da mikrobiyal yapı ve beslenme şekli, özellikle ağrı ve kabızlık semptomlarında iyileşme ile ilişkili bulunmuştur. Psikolojik stres düzeyi yüksek olan kişilerde ise şişkinlik şikayetinde iyileşme daha az olmuştur. Başlangıçta daha hafif semptomlara (yüksek kalori alımı olan, disbiyoz skoru düşük olan) sahip bireylerde anlamlı bir iyileşme gözlemlenmiştir. Ancak başlangıçta daha fazla FODMAP tüketen hastalar, geleneksel İBS diyetine daha iyi yanıt verirken düşük FODMAP diyetinde bu etki gözlenmemiştir. Hatta başlangıçta yüksek FODMAP tüketen hastalar düşük FODMAP diyeti sırasında şişkinlikte daha kötü yanıt göstermiştir. Eğer bir hasta günlük hayatında FODMAP'leri rahatsız edici bulmuyor ve bunlardan kaçınmıyorsa, çok katı bir diyet olan düşük FODMAP diyeti ona fayda sağlamayabilir (Colomier vd., 2022). En sık tüketilen oligosakkarit kaynaklarından biri olan buğday, İBS belirtilerinin en yaygın tetikleyicilerinden biridir. Ancak buğday bileşenlerinden hangisinin (fruktan veya gluten) IBS semptomlarına katkıda bulunduğu henüz açıklığa kavuşturulmamıştır (Bellini vd., 2020). Glutensiz beslenme, aynı zamanda fruktooligosakkaritlerin ve tahıla özgü bazı bileşenlerin alımını da sınırlandırmaktadır. Glutensiz bir diyet uygulanırken fruktan tüketiminin azaltılması, karın ağrısı gibi belirtilerde belirgin bir rahatlama sağlayabilir (Mohseni vd., 2022). İBS olan bireyler, özellikle diyare ağırlıklı alt tipe sahip olanlar, süt ve süt ürünleri gibi laktoz içeren besinleri tükettikten sonra semptomlarında artış yaşadıklarını fark ettikleri için bu tür gıdalardan kaçınma eğilimindedir. Bu nedenle pek çok İBS hastası, kendi deneyimlerine dayanarak süt ürünlerini tolere edemediklerini düşünmekte ve laktoz intoleransını kesin bir tanı olmaksızın varsayarak laktozsuz ürünlere yönelmektedir. Ancak, İBS hastalarında bildirilen laktoz intoleransı sağlıklı bireylere kıyasla daha yaygın görünse de, bu durum her zaman gerçek bir laktoz malabsorpsiyonuna bağlı olmayabilir (Özyürek vd., 2023). Krieger ve arkadaşlarının gerçekleştirdiği bir çalışmada 29 İBS hastası rastgele iki gruba ayrılarak biri düşük FODMAP diyeti, diğeri ise düşük laktozlu diyet uygulamak üzere müdahale sürecine alınmıştır. Müdahaleler 14 gün sürmüş, ardından 21 günlük bir arınma süresi verilerek gruplar diyetleri değiştirip yeniden uygulanmıştır. Çalışmanın sonunda her iki diyetin de İBS semptomlarını genel olarak anlamlı düzeyde azalttığı gözlemlenmiştir. Bununla birlikte, düşük FODMAP diyetinin, laktozsuz diyete kıyasla ağrı ve şişkinlik gibi belirli semptomların giderilmesinde daha etkili olduğu bulunmuştur (Krieger vd., 2020). Çift kör, randomize ve plasebo kontrollü bir klinik çalışmada İBS olan bireylerde düşük FODMAP içeren glutenli ve glutensiz diyetlerin semptomlar üzerindeki etkisi incelenmiştir. Altı hafta süren çalışmada, kontrol grubuna günlük 5 gram pirinç unu içeren düşük FODMAP diyeti uygulanırken, müdahale grubuna aynı miktarda gluten tozu verilmiştir. Bulgular, FODMAP'lerin diyetten çıkarılmasının çoğu hastada semptomları hafiflettiğini göstermiştir. Gluten içeren düşük FODMAP diyetinin ise genel olarak İBS hastalarında semptomlar veya yaşam kalitesi üzerinde olumsuz bir etkisi olmadığı belirlenmiştir. Bununla birlikte, hastaların yaklaşık %20'sinde glutenin doğrudan semptomların

nedeni olabileceği görülmüştür. Buğday ve arpanın İBS semptomlarını genellikle içerdiği fruktanlar nedeniyle tetiklediği, glutenin ise yalnızca daha küçük bir hasta grubunda etkili olduğu anlaşılmıştır. Bu sonuçlar, bazı İBS hastalarında çölyak dışı gluten hassasiyeti olabileceği görüşünü desteklemektedir. Düşük FODMAP diyetinin uygulanmasının zorlukları göz önünde bulundurulduğunda, özellikle Asya toplumları gibi yüksek FODMAP içeren gıdaların sıkça tüketildiği bölgelerde, bu diyete başlamadan önce bireylerde gluten duyarlılığının değerlendirilmesi önerilmektedir (Mohseni vd., 2022). İBS hastalarının bir kısmında visseral aşırı duyarlılık bulunmaktadır. Bu durum, aynı büyüklükteki (örneğin, gaz, şişkinlik ya da basınç gibi) uyarıların, bazı bireylerde daha güçlü semptomlara (ağrı, rahatsızlık) neden olabileceğini göstermektedir. İBS de düşük ve orta düzeyde FODMAP içeren diyetlerin GI semptomlar üzerindeki etkilerini karşılaştırmak amacıyla yürütülen çift kör, randomize, kontrollü bir çalışmada genel GI semptomlarının şiddeti, karın ağrısı yoğunluğu ve sıklığı, bağırsak alışkanlıklarından memnuniyetsizlik ve günlük yaşama etkisi IBS-D hastalarında diğer alt gruplara göre düşük FODMAP döneminden sonra azalmış, ancak orta FODMAP döneminden sonra azalmamıştır. Düşük FODMAP döneminden sonra, daha sert dışkı ve azalmış bir dışkı sıklığı kaydedilmesine rağmen orta FODMAP döneminde böyle bir etki görülmemiştir. Bu bulgular, düşük FODMAP diyetinin, IBS-C olanlara kıyasla IBS-D ve/veya IBS-M olan IBS hastalarında daha etkili olabileceğini göstermektedir; bu da önceki çalışmalarla uyumludur. FODMAP'a hassas olan kişiler FODMAP'a hassas olmayanlara göre düşük FODMAP sırasında daha kötü semptomlar yaşadığı tespit edilmiştir. Bunun muhtemel nedeni ise visseral hipersensitivite olduğunu düşünülmektedir (Algera vd., 2022). Gluten hassasiyeti, İBS olan bireylerin en sık dile getirdiği gıda kaynaklı yakınmalardan biridir. Bazı İBS hastalarında çölyak hastalığı bulunmamasına rağmen gluten alımı sonrasında intolerans benzeri belirtiler gözlemlenmiştir. Bu durum, glutenin İBS semptomlarını tetikleyebileceği düşüncesiyle glutensiz beslenme yaklaşımlarının önerilmesine neden olmuştur. Ancak, bu hassasiyetin çoğu zaman bağışıklık sistemi aracılığıyla değil, farklı mekanizmalarla geliştiği düşünülmektedir. Özellikle, bu semptomların, glutenle birlikte tüketilen ve bağırsakta tam sindirilemeyen fruktan adlı karbonhidratlara karşı gelişen bir intoleranstan kaynaklanabileceği öne sürülmektedir (Dionne vd., 2018). LFD ve GFD'nin TDA'ne kıyasla IBS semptomlarını iyileştirmede daha etkili olup olmadığını araştırmak için yapılan bir çalışmada diyetlerin klinik etkinlikte önemli ölçüde farklılık göstermediği belirtilmiştir. Mevcut çalışmada GFD grubunda çapraz kontaminasyon göz ardı edilmiş olup diğer yayınlar IBS'de GFD'nin çölyak hastalığında görülen kadar katı olması gerekmediğini öne sürmektedir. Makrobesinler ve mikrobesinler her bir diyet grubunda azalmış olsa da, GFD ve TDA ile karşılaştırıldığında LFD'de daha fazla lif azalması dışında gruplar arasında önemli bir fark görülmedi. LFD'nin TDA ve GFD ile karşılaştırıldığında disforide önemli bir iyileşme göstermesi dışında gruplar arasında farklılık gözlenmemiştir (Rej vd., 2022). Çeşitli araştırmalar, semptomların glikozdan ziyade oligofruktoz veya fruktoz tüketimiyle daha fazla ilişkili olduğunu ortaya koymuştur. Ayrıca, laktoz, fruktoz, fruktooligosakkaritler ve sorbitol gibi bireysel FODMAP bileşenleri; şişkinlik, karın ağrısı, mide bulantısı ile birlikte dışkılama sıklığında artış ya da azalma gibi IBS hastaları tarafından sıkça bildirilen semptomlara yol açabilmektedir (Major vd., 2017). Küçük ölçekli bir çalışmada, nefes testleri yoluyla fruktoz intoleransının işlevsel şişkinlik ve gazla ilişkili yakınmaların en yaygın nedeni olduğu gösterilmiştir. Bu doğrultuda, hastaların yaklaşık %65'inde karbonhidrat emilim bozukluğu saptanmış, bir aylık diyet kısıtlamasının ardından %80'den fazlasında semptomların azaldığı belirlenmiştir. Tedavinin bir yıl sürdürülmesiyle birlikte katılımcıların %50'sinde tamamen semptom kontrolü sağlanmıştır (Moshiree vd., 2023) . Çok sayıda klinik araştırma, özellikle karın şişkinliği gibi belirtilerin yönetiminde düşük FODMAP diyetinin etkili olduğunu göstermiştir; bu diyete uyan IBS hastalarının yaklaşık %50 ila %75'inde belirgin bir iyileşme sağlandığı bildirilmiştir (Mitchell vd., 2019).

Kolon bakterileri tarafından lüminal bağırsakta gerçekleşen fermantasyon, gazların (hidrojen, metan ve karbondioksit) yanı sıra ikincil yan ürünler olarak kısa zincirli yağ asitleri (SCFA) ve dallı zincirli yağ asitlerinin (BCFA) oluşumuna yol açar. Düşük FODMAP diyetinde fermantasyondaki varsayılan azalma teorik olarak SCFA üretiminde bir azalmaya yol açmalıyken, FODMAP' lerin dışkı SCFA'ları üzerindeki tutarsız etkileri gözlemlenmiştir. Yapılan son sistematik inceleme, düşük FODMAP diyeti ile kontrol diyetleri arasında toplam dışkı SCFA konsantrasyonunda hiçbir fark veya belirli SCFA'ların dışkı konsantrasyonlarında veya dışkı pH'ında hiçbir fark bulamamıştır (So vd., 2022). Bu durumun aksine IBS için Geleneksel Diyet Tedavisine kıyasla Akdeniz tarzı düşük FODMAP Diyeti'nin (MED-LFD) etkinliğini ve dışkı uçucu bileşik seviyelerindeki değişiklikleri değerlendirmek için yapılan bir çalışmada her iki grupta da IBS-SSS'de anlamlı bir azalma gözlemlendi. Ancak MED-LFD grubundaki hastalar TDA grubuna kıyasla yaklaşık iki kat semptom iyileşmesi göstermiştir. Çalışma, beslenme müdahalesinin dışkıdaki SCFA ve BCFA düzeylerini azalttığını göstermiştir. Bu durum, tedavi başarısının potansiyel bir göstergesi olabilir. MED-LFD grubunda dışkı formlarında ve anksiyete, depresyon ölçeklerinde anlamlı iyileşmeler olduğu vurgulanmıştır (Kasti vd., 2025).

DÜŞÜK FODMAP DİYETİ VE BAĞIRSAK MİKROBİYOTASI

Kalın bağırsaktaki mikrobiyota, sindirilmeden oraya ulaşan karbonhidratları fermente ederek gaz ve biyolojik olarak aktif metabolitler üretir. Bu nedenle, bağırsak mikrobiyota profili, düşük FODMAP diyetine verilen yanıtı etkileyen temel faktörlerden biri olarak öne sürülmüştür. Yetişkin IBS hastalarında, düşük FODMAP diyetine yanıt vermeyenlerin bağırsak mikrobiyotası başlangıçta daha yüksek bir disbiyoz indeksi taşımaktadır. Bu kişilerde özellikle IBS ile ilişkili olduğu bilinen Dorea, Ruminococcus gnavus ve Streptococcus türlerinin göreceli oranı daha yüksektir. Bunun ardından yapılan çok sayıda çalışmada, diyete olumlu yanıt verecek mikrobiyal profili tanımlamak hedeflenmiştir, ancak bu konuda hâlâ açık ve tutarlı bir model bulunamamıştır (De Palma ve Bercik, 2022). Bazı ilk çalışmalarda, sadece diyete yanıt vermeyen kişilerde belirli bakterilerin arttığı görülmüştür. Ama daha sonraki araştırmalarda, diyete iyi yanıt veren kişilerde bile bu bakterilerin fazla olduğu tespit edilmiştir: Bacteroides fragilis, Acinetobacter, Ruminiclostridium, Streptococcus, Eubacterium (Zhang vd., 2021). Birçok çalışma, fermente olabilen karbonhidratların kısıtlanmasının, probiyotik etkileriyle bilinen faydalı Bifidobacterium türlerinin miktarını azalttığını kabul etmektedir. Bifidobacteria adı verilen faydalı bakteriler, fruktanlar gibi bazı lif türlerini kullanarak yaşarlar. Bu lifleri parçalama ve sindirme özellikleri onların metabolik yetenekleridir. Ancak düşük FODMAP diyeti fruktanları da kısıtladığı için, bu bakterilerin besin kaynağı azalır. Dolayısıyla bu bakterilerin sayısında da azalma olur. Bu durum uzun vadede zararlı olabilir. Bu durumun önüne geçmek için bazı klinik çalışmalar, düşük FODMAP diyetinin neden olduğu Bifidobakterium azalmasını önlemek için probiyotik veya prebiyotik takviyeleri test etmiştir (De Palma ve Bercik, 2022). Prebiyotik takviyesi, Bifidobakterium kaybını engelleyememiştir; ancak probiyotik takviyesi, Bifidobacterium türlerini başlangıç seviyelerinde koruyabilmiştir (Wilson vd., 2020). Staudacher ve arkadaşlarının yaptığı bir çalışma, diyetisyen rehberliğinde ve gözetiminde uygulanan düşük FODMAP diyetinin, uzun vadede bifidobakterileri olumsuz etkilemediğini, ancak bağırsaktaki SCFA üretimini değiştirebileceğini göstermiştir (Staudacher vd., 2022). Düşük FODMAP-Glutensiz diyetin 6 haftalık müdahale süresi boyunca (LF-GFD) IBS'li İranlı hastalarda klinik semptomlar, bağırsak mikrobiyotası çeşitliliği ve dışkı kalprotektin (FC) düzeyine etkileri değerlendirilmiştir. IBS hastalarında yapılan mikrobiyota analizlerinde, diyet öncesinde Firmicutes filumunun Bacteroidetes filumuna göre baskın olduğu gözlemlenmiştir. Diyet müdahalesi sonrasında ise Bacteroidetes filumunda artış meydana gelmiş ve buna bağlı olarak Firmicutes/Bacteroidetes (F/B) oranında bir azalma

kaydedilmiştir. Ayrıca Actinobacteria, Bifidobacterium ve Lactobacillus cinslerine ait bakteriler de artış gözlemlenmiştir. Ancak bazı çalışmalarda, IBS hastalarında IBS olmayan bireylere kıyasla Bacteroidetes ve Actinobacteria filumlarının göreli bolluğunda artış olduğu bildirilmiştir. Ayrıca, düşük FODMAP içeren diyetlerin IBS hastalarında, glutensiz diyetlerin (GFD) ise çölyak hastalarında Bifidobacterium düzeylerini azalttığı gösterilmiştir. Bu bulgular, bağırsak mikrobiyotasındaki değişikliklere ilişkin çelişkili sonuçlar ortaya koymaktadır. Çalışmada, hastaların yarısından fazlasında diyet müdahalesinden önce anormal FC değerleri (çoğunlukla IBS-D alt grubunda) vardı. Mikrobiyotada meydana gelen değişikliklerin IL-6 ve IL-8 gibi proinflamatuar sitokinleri indükleyebileceği ve bu nedenle hastaların kronik düşük dereceli inflamasyondan muzdarip olabileceği bildirilmiştir. Sonuç olarak LF-GFD tüketimi ile FC azalması arasında anlamlı bir korelasyon mevcuttur (Naseri vd., 2021).

FODMAP DİYET TEPKİ BELİRTEÇLERİ

IBS tedavisinde diyetin başarısını artırmak için, hangi hastaların bu diyetten daha fazla fayda görebileceğini belirlemeye yönelik çalışmalar yapılmıştır. Bu kapsamda, diyet tedavisine verilecek yanıtı önceden tahmin edebilecek bazı faktörleri belirlemeye yönelik araştırmalar yürütülmüştür (Black vd., 2022).

Nefes Testi

FODMAP içeren yiyeceklerin bağırsakta fermantasyonu sonucu oluşan H_2 gazı nefes yoluyla ölçülmesiyle elde edilir. Yapılan bir çalışmada katılımcılara yüksek FODMAP içeren bir öğün verilmiştir. Ardından, katılımcıların nefesindeki hidrojen gazı seviyesi ölçülmüştür. Eğer bu seviye, başlangıç değerinin 10 PPM üzerinde artıyorsa ve kişi aynı zamanda semptom (gaz, şişkinlik, ağrı vs.) yaşıyorsa, bu "pozitif test" olarak kabul edilmiştir. Bu test, kişinin düşük FODMAP diyetinden fayda görüp görmeyeceğini tahmin etmekte %78,6 duyarlılık, %66,6 özgüllük, %75,6 doğruluk ile ortalama bir başarı göstermiştir (Ghoshal vd., 2020).

Dışkı ve İdrar Metabolitleri

Dışkı uçucu organik bileşiklerinin spesifik profilleri, düşük FODMAP diyetine yanıtı tahmin etmede dikkate değer bir doğruluk sergilemiştir. Bireyin düşük FODMAP diyetinden fayda görüp görmeyeceği, diyet başlamadan önce dışkı ve idrar analizleriyle tahmin edebilir (Ricco vd., 2018). Wilson ve arkadaşlarının yürüttüğü yakın tarihli, çift kör randomize kontrollü bir çalışmada, IBS hastalarına plasebo bir diyet veya düşük FODMAP diyeti uygulanmıştır. Çalışma, başlangıçta dışkıda bulunan bazı metabolitlerin (yüksek düzeyde propiyonat ve sikloheksan karboksilik asit esterleri) ve idrardaki metabolitlerin, düşük FODMAP diyetine yanıt veren hastaları ayırt edebildiğini ve bu sonuçların önceki bulgularla uyumlu olduğunu göstermiştir (Wilson vd., 2023). Ancak yakın zamanda Birleşik Krallık'ta yapılan bir çalışma aynı başarıyı gösterememiştir. Bu durum, bu alandaki belirsizliği ortaya koymakta ve düşük FODMAP diyetinin bağırsak mikrobiyotası üzerindeki etkileri konusunda daha fazla araştırma yapılması gerektiğini vurgulamaktadır.

Mikrobiyota Analizleri

Düşük FODMAP diyetine başlama bağlamında tedavi yanıtlarının potansiyel öngörücüleri arasında belirli bakterilerin bileşimi ve zenginliği yer almaktadır. Ancak çalışmalarda bireysel mikrobiyal türlerle ilgili çelişkili sonuçlar mevcut olduğundan gelecekteki araştırmalarla bu durumun açıklığa kavuşturulması gerekmektedir.

Düşük fodmap diyetinin dezavantajları

Sosyal ve Yaşam Tarzı Zorlukları

Özellikle, düşük FODMAP diyetinin ilk aşaması sosyal durumlarda zorluklara yol açabilir ve titiz bir yemek planlaması gerektirebilir, bu da bazı bireyler için yaşam tarzı karmaşıklıklarını beraberinde getirir. IBS hastalarının yer aldığı ve katılımcıların rastgele şekilde düşük FODMAP diyeti veya kontrol diyeti gruplarına atandığı iki randomize kontrollü çalışmanın ikincil analizinde, araştırmacılar uzman bir diyetisyen eşliğinde uygulanan 4 haftalık düşük FODMAP diyetinin toplam besin alımı ya da diyet çeşitliliği üzerinde anlamlı bir etkisi olmadığını belirlemiştir. Bununla birlikte, kontrol diyetleriyle karşılaştırıldığında düşük FODMAP diyetinin genel diyet kalitesini azalttığı görülmüştür. Diyet kalitesi, Sağlıklı Diyet Göstergesi ve Sağlıklı Diyet Puanı gibi ölçütlerle değerlendirilmiştir (Staudacher vd., 2020). IBS hastalarında TDA, düşük FODMAP diyeti ve GFD'nin etkinliğini ve tatmin ediciliğini karşılaştıran yakın tarihli bir karşılaştırmalı RCT'de, kişiler TDA'nın daha uygun maliyetli olduğunu, alışveriş için daha az zaman gerektirdiğini ve düşük FODMAP diyetine kıyasla günlük yaşamda takip edilmesinin ve uygulanmasının daha kolay olduğunu bildirdiler (Rej vd., 2022).

Beslenme Rehberliği

Düşük FODMAP diyetinden en iyi sonuçları elde edebilmek, diyetin karmaşıklığı ve yüksek gıda maliyetleri gibi zorlukların üstesinden gelebilmek, uygun alternatif gıdaları belirlemek ve diyet uyumunu artırmak için bir diyetisyenle iş birliği yapılması oldukça önemlidir. Ancak bazı sağlık merkezlerinde diyetisyen desteğine kolayca ulaşılamaması, farklı eğitim yöntemlerinin işe yarayıp yaramayacağı konusunu gündeme getirmektedir. Güncel randomize kontrollü bir çalışmada, fonksiyonel gastrointestinal bozuklukları olan hastalara düşük FODMAP diyeti kapsamında üç farklı eğitim yöntemi sunulmuştur: kitapçık, mobil uygulama ve diyetisyen danışmanlığı. Sonuçlar, diyetisyen rehberliğinde eğitim alan bireylerin, semptomlarını bağımsız şekilde kontrol etmede kendilerini daha yetkin hissettiklerini göstermiştir (Dimidi vd., 2023).

Beslenme Eksiklikleri

Son dönemde yapılan çalışmalar, düşük FODMAP diyetinin besin açısından yeterliliğini değerlendirmeye odaklanmıştır. Bu alandaki bulgular tutarsızlık göstermektedir; özellikle karbonhidrat alımının azalmasına bağlı olarak en sık karşılaşılan yetersizliklerden biri lif tüketiminde azalmadır. Süt ürünlerinin aşırı düzeyde diyetten çıkarılması, kalsiyum alımında azalmaya neden olabilirken; sebze ve meyve tüketimindeki kısıtlamalar, B1, B2, B9 ve D vitaminlerinde yetersizlikle ilişkilendirilmektedir. Ayrıca demir eksikliği vakaları da bildirilmiştir. Enerji alımındaki düşüşe bağlı olarak kilo kaybı da görülebilmektedir. Her ne kadar düşük FODMAP diyetine dair uzun vadeli etkiler konusunda yeterli veri bulunmasa da, bu diyetin sağlık uzmanları tarafından izlenerek uygulanması, olası besin eksikliklerinin önlenmesine yardımcı olabilir (Berfin vd., 2024). Modifiye edilmiş NICE diyeti ile düşük FODMAP diyetini 4 haftalık bir süre boyunca karşılaştıran bir randomize kontrollü çalışmanın post hoc analizinde, düşük FODMAP diyeti uygulayan katılımcıların günlük kalori alımında ve bazı temel mikrobesin düzeylerinde azalma gözlemlenmiştir. Ancak, kalori alımındaki değişiklikler dikkate alınarak yapılan değerlendirmede, yalnızca riboflavin düzeyindeki düşüş istatistiksel olarak anlamlı bulunmuştur (Eswaran vd., 2020). Uzun vadeli bulgular, düşük FODMAP diyetinin beslenme açısından yeterli olabileceğine işaret etmektedir. Son araştırmalar, uzun süreli uygulamalarda düşük FODMAP diyeti ile geleneksel beslenme düzeni arasında besin öğeleri açısından anlamlı bir fark bulunmadığını göstermektedir (Rej vd., 2021)

. Zamanla düşük FODMAP diyeti uygulayan bireylerde toplam enerji ve makro besin alımında azalma gözlenmiş olsa da, bu durum genellikle IBS hastalarının değişen yeme davranışlarıyla ilişkilidir. Birçok IBS hastasının önerilen beslenme hedeflerini karşılayamaması, bu düşüşün altında yatan temel nedenlerden biridir. Ayrıca, bu gruptaki besin eksikliklerinin başlıca sebepleri arasında yetersiz beslenme danışmanlığı ve bireylerin kendi kendine uyguladığı kısıtlamalar yer almaktadır (Eswaran vd., 2020).

Konstipasyon

Düşük FODMAP diyetinin potansiyel dezavantajlarından biri, lif alımının sınırlanması nedeniyle kabızlık semptomlarının kötüleşme riskidir. Bu durum özellikle liften zengin FODMAP içeren gıdaların diyetten çıkarılmasıyla ilişkili olabilir. So ve çalışma arkadaşlarının yürüttüğü yakın tarihli bir randomize çapraz tasarımlı araştırmada, IBS tanısı almış bireyler, yalnızca lif içeriği açısından farklılık gösteren üç farklı düşük FODMAP diyetini uygulamıştır. Araştırma bulgularına göre, düşük FODMAP diyeti süresince lif takviyesi yapılmasının bireylerin bağırsak hareketlerine dair algılarında belirgin bir değişiklik oluşturmadığı görülmüştür. Bununla birlikte, kontrol diyetleriyle karşılaştırıldığında dışkının su içeriğinde artış ve kolon geçiş süresinde normalleşme gibi olumlu etkiler gözlemlenmiştir (So vd., 2022).

Yeme Bozuklukları ve Psikiyatrik Eşlik Eden Durumlar

Düşük FODMAP diyetinin başlangıç aşamasındaki kısıtlamalar, hastaların duygusal iyilik hali üzerinde olumsuz etkiler yaratabilir. İBS semptomlarının kötüleşme ihtimali ve diyet kısıtlamalarıyla ilgili endişeler, anksiyete düzeylerinde artışa yol açarak yeme bozukluklarının ortaya çıkmasına zemin hazırlayabilir (Sultan vd., 2022). Özellikle, kaçınmacı-kısıtlayıcı yeme bozuklukları ile ortoreksiya nervoza, düşük FODMAP diyeti uygulayan bireylerde en sık görülen yeme bozuklukları arasında yer almaktadır. Bu nedenle, yeme bozukluğu öyküsü olan kişilere düşük FODMAP gibi kısıtlayıcı diyetlerden kaçınmaları önerilmektedir. Ayrıca, bu bireylerde yetersiz beslenme riskini değerlendirmek amacıyla ön tarama yapılması faydalı olacaktır (Bellini vd., 2020). Bunun yanı sıra, bilişsel kısıtlamalar ve ağır psikiyatrik hastalıklar, hastaların kendileri için önemli olan yiyecek tetikleyicilerini belirlemelerini, kısıtlayıcı diyetlere uyum sağlamalarını ve klinik yanıtlarını doğru şekilde raporlamalarını güçleştirebilir (Bertin vd., 2024).

SONUÇ VE ÖNERİLER

Düşük FODMAP diyeti İBS yaşayan bireylerde semptomların (karın ağrısı, şişkinlik, kabızlık, ishal vs.) azaltılmasında etkili ve güvenilir bir yöntem olarak öne çıkmaktadır. Uzun süreli veriler ne kadar yetersiz olsa da (potansiyel besin eksiklikleri ve bağırsak mikrobiyomu üzerindeki etki) bireyin semptomlarını uzun vadede daha etkili şekilde yönetmesine yardımcı olmakta ve yaşam kalitesini arttırmaktadır. Düşük FODMAP diyeti FODMAP içeren besinlerin diyetten sınırlı bir süre çıkartılıp tekrar tanıtıldığı aşamalı ve beslenme uzmanı tarafından sıkı takip gerektiren bir diyettir. FODMAP diyeti uygulanırken, beslenme dengesinin korunması ve vücudun ihtiyaç duyduğu tüm besin öğelerinin yeterli şekilde alınabilmesi için bu sürecin bir diyetisyen eşliğinde yürütülmesi büyük önem taşır. Günümüzde İBS'nin yönetiminde en etkili yaklaşımlar, ilaç tedavisi, beslenme düzenlemeleri ve psikolojik destek gibi çeşitli yöntemlerin bir arada kullanıldığı bütüncül bir bakım modelini önermektedir. Düşük FODMAP diyetinin etkinliği, özelleştirilebilirliği onu İBS'den (özellikle İBS-D) kurtulmak isteyenler için umut vadeden bir seçenek haline getirmektedir. Uzun vadeli etkinlik ve uyumla ilgili bilgiler şu anda kısıtlı olsa da gözlemsel çalışmalardan elde edilen ilk bulgular umut vadetmektedir. Gelecekte yapılacak uzun süreli daha çok çalışmaya ihtiyaç duyulmaktadır.

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NANO SİLİSYUMUN TUZ STRESİ ALTINDA KAVUN GENOTİPLERİNDE ÇİMLENME VE FİDE GELİŞİMİNE ETKİSİ

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ÖZET

Tuz stresi çimlenme, bitki büyüme ve gelişimini olumsuz etkileyen en önemli abiyotik stress koşullarından biri olarak değerlendirilmektedir. Silisyum temel bir besin maddesi olarak geniş çapta tanınmamakla birlikte, genellikle bitki büyümesi, fizyolojik/metabolik yolak, hücre yapısı ve çok çeşitli abiyotik ya da biyotik çevresel streslerin hafifletilmesi için yararlı olan "değerli bir element" veya "yapısal element" olarak kabul edilmektedir. Birçok çalışma farklı bitki türlerinde tuzluluk, ağır metal stresi, kuraklık gibi abiyotik stres koşullarında bitki büyüme ve gelişmesi ile verimi artırmadaki rolünü doğrulamıştır. Bu çalışmada, nano silisyum (NSi) uygulamalarının tuz stresi koşullarında CU40 (hassas) ve CU159 (tolerant) kavun genotiplerinde çimlenme oranı, çimlenme zamanı, çıkış oranı ve hızı, radikul yaş ağırlığı ile fide gelişimi üzerindeki etkileri değerlendirilmiştir. Bu amaçla tuz stresi 150 mM düzeyinde uygulanırken; Nano-Si (NSi) uygulaması için; 0.5 ve 1 mM olmak üzere 2 farklı konsantrasyon çalışmaya dahil edilmiştir. İncelenen tüm parametreler bakımından kontrol bitkilerine oranla azalma meydana gelirken çimlenme hızı tuz stresi ile birlikte artış göstermiş, bu artış hassas CU40 genotipinde belirginleşmiştir. NSi uygulamaları tuz stresinin olumsuz etkisini her iki genotipte de sınırlandırmıştır. Bununla birlikte çimlenme hızı %6-20 oranında iyileşmiştir. Fide yaş ve kuru ağılıkları stres koşullarında kontrol bitkilerine oranla %26-71, kök yaş ve kuru ağılıklarında %43-76 oranında azalırken; NSi uygulamalarında bu oran fide yaş ve kuru ağırlıklarında %13-46, kök yaş ve kuru ağırlıklarında ise %22-54 oranında meydana gelmiştir. NSi uygulamaları kavunda çimlenme, çıkış ve fide gelişimi bakımından tuz stresinin olumsuz etkilerini sınırlandırmada etkili olmuş, bu etki 0.5 mM NSi uygulamasında daha belirgin gerçekleşmiştir.

Anahtar Kelimeler: *Cucumis melo* L., Çimlenme, Genotip, Nanosilisyum, Tuzluluk

EFFECTS OF NANO-SILICON ON GERMINATION AND SEEDLING DEVELOPMENT OF MELON GENOTYPES UNDER SALT STRESS

ABSTRACT

Salt stress is considered one of the major abiotic stress factors that adversely affect seed germination, plant growth, and development. Although silicon (Si) is not widely recognized as an essential nutrient, it is commonly regarded as a “beneficial” or “structural” element due to its positive effects on plant growth, physiological/metabolic pathways, cell structure, and its ability to alleviate a broad range of abiotic and biotic stresses. Numerous studies have confirmed its role in enhancing plant growth, development, and yield under various abiotic stress conditions such as salinity, heavy metal toxicity, and drought across different plant species. In this study, the effects of nano-silicon (NSi) treatments on germination percentage, germination time, emergence rate and speed, hypocotyl fresh weight and length, and seedling development were evaluated in two melon genotypes CU40 (sensitive) and CU159 (tolerant) under salt stress. Salt stress was imposed at 150 mM NaCl, while NSi treatments were applied at two concentrations: 0.5 and 1 mM. Compared with the control, all examined parameters decreased under salt stress; however, germination speed increased, particularly in the sensitive genotype CU40. NSi treatments mitigated the adverse effects of salt stress in both genotypes, improving germination time by 6–20%. While seedling fresh and dry weights decreased by 26–71% and root fresh and dry weights by 43–76% under stress compared to the control, these reductions were limited to 13–46% (seedling fresh/dry weight) and 22–54% (root fresh/dry weight) with NSi applications. Overall, NSi treatments were effective in reducing the negative impacts of salt stress on germination, emergence, and seedling development in melon, with the 0.5 mM NSi concentration showing more pronounced benefits.

Keyword: *Cucumis melo* L., Germination, Genotype, Nanosilicon, Salinity

INTRODUCTION

The progressive expansion of soil salinization has become a major constraint on crop performance, threatening both agricultural productivity and ecological sustainability. Each year, approximately 10% more arable land becomes affected by salt accumulation. Soils classified as saline typically exhibit an electrical conductivity above 4.0 dSm^{-1} (roughly equivalent to 40 mM NaCl), a condition that markedly interferes with plant growth and physiological functioning (Liu et al., 2024). Exposure to salinity alters plants' morphological, biochemical, and physiological traits, ultimately leading to reduced yield potential (Achary et al., 2024). As the salt concentration in the rhizosphere increases, plants tend to accumulate excessive sodium (Na^+) and chloride (Cl^-) ions. Of these, chloride ions are particularly detrimental, as they trigger osmotic imbalance, ion toxicity, and nutrient deficiency within plant tissues (Singh et al., 2024).

Seed germination in halophytic species is also adversely affected by high salinity, as many of these plants prefer to germinate in fresh water or under very low salt concentrations. The inhibitory effect of salinity on germination may result from ion toxicity or osmotic stress caused by a reduction in water potential around the seeds. This increase in the osmotic pressure of the soil solution limits water uptake, thereby delaying or preventing the initiation of germination. Furthermore, excessive intracellular accumulation of salts can deactivate key enzymes required for germination and hinder the release from seed dormancy (Al-Janabia et al., 2024).

Nanoparticles (NPs), also known as nano-scale particles (NSPs), are small particles with sizes ranging from 1 to 100 nm. These particles have gained significant attention in agricultural applications, functioning as growth stimulants, herbicidal agents, nano-pesticides, and nano-fertilizers. When applied in small quantities, nano-fertilizers enhance nutrient use efficiency and mitigate the toxic effects that often result from the excessive accumulation of conventional chemical fertilizers and pesticides in the soil. In addition, they play a crucial role in strengthening plants' resistance to both abiotic and biotic stresses by modulating key physiological and biochemical pathways (DeRosa et al., 2010; Siddiqui et al., 2015; Saxena et al., 2016).

In this study, the effects of NSi seed applications on germination and early seedling development in melon genotypes that are tolerant and sensitive to salt stress were investigated.

MATERIAL AND METHOD

In this study, salt-tolerant (CU159) and salt-sensitive (CU40) melon genotypes were used as plant materials (Kusvuran et al., 2010). A 150 mM NaCl treatment was applied to induce salt stress. Germination tests were conducted in petri dishes between filter papers with four replications, each consisting of 25 seeds. Emergence tests were performed by sowing 25 seeds per replication into peat-filled seedling trays, also arranged in three replications. Both germination and emergence experiments were carried out under controlled climate chamber and greenhouse conditions at 25 °C with a photoperiod of 16 h light and 8 h dark. Melon seeds that produced a radicle at least equal to the seed length were considered germinated and counted daily for eight days. In emergence tests, seedlings that reached the peat surface and developed cotyledons were recorded daily for ten days.

Germination and emergence percentages were calculated as proportions (%), while germination and emergence times were determined in "days" according to ISTA (1993) and Öztürk et al. (2021). In addition, hypocotyl fresh weight, hypocotyl length, and radicle length were measured. Melon seeds subjected to different NSi treatments were sown in seedling trays filled with a peat:perlite (2:1) mixture under greenhouse conditions to evaluate seedling

characteristics. The experiment was conducted with three replications, each consisting of 25 plants. At the end of the study, emergence percentage, emergence speed, and seedling fresh and dry weights (g plant^{-1}) were determined.

Statistical analyses were performed using the JMP software package based on a completely randomized design with three replications. The effects of the treatments were evaluated through analysis of variance (ANOVA), and differences among means were compared using the Least Significant Difference (LSD) multiple comparison test.

RESULTS AND DISCUSSION

Saline environments negatively affect both the speed of seed germination and the uniformity of seedling growth. Consequently, seed priming has emerged as a practical pre-sowing strategy to improve seed adaptation under stress conditions. This technique enhances stress tolerance by promoting early metabolic activation, boosting antioxidant defenses, and increasing the accumulation of beneficial metabolites all of which contribute to improved crop performance. Treating seeds with growth-promoting agents prior to exposure to adverse conditions induces a form of stress memory. This physiological imprinting enables primed seeds to better withstand environmental constraints during germination, seedling establishment, and subsequent growth stages. Recent findings from nanopriming studies demonstrate that, compared with conventional priming approaches, the use of nanoparticles (NPs) accelerates water uptake and promotes faster radicle emergence (Hameed et al., 2021; Singh et al., 2024).

In the study, salt stress reduced germination percentage in both genotypes, while germination time increased under stress conditions. However, with the application of NSi, germination percentage improved by 17–61%, and germination time decreased by 25–46%. Similarly, emergence percentage decreased by 46% in the CU40 genotype and by 29% in the CU159 genotype under salt stress; with NSi treatments, this reduction was limited to 9–17%. The highest hypocotyl fresh weight in control plants was recorded in the CU40 genotype at 0.40 g. The longest hypocotyl length was observed in the CU159 genotype (8.16 cm), while the greatest root length was recorded in CU40 (15.58 cm). Salt stress caused a reduction of approximately 22–75% in hypocotyl fresh weight, hypocotyl and root length, with the greatest decrease observed in the CU40 genotype. With NSi treatments, improvements of 16–107% were achieved, reducing the negative effects of salt stress to only 2–55% compared to control plants (Figure 1). In tomato, NSi powder significantly improved germination parameters such as germination percentage, germination index, vigor index, mean germination time and average shoot length of tomato (Lu et al., 2015). Alsaeedi, et al. (2019) indicated that the effects of five rates of nano-silica (NSi) suspensions (0, 100, 200, 300 and 400 mg L^{-1}) on cucumber (*Cucumis sativus*) seed germination and growth development, it was reported that 200 mg L^{-1} rate significantly increased the final germination percentage, germination speed, viability index and germination index by 28.7%, 70.3%, 46.7% and 68.8%, respectively, compared to untreated seeds, and reduced the average germination time by 31.7%. Similarly, 200 mg L^{-1} NSi had the highest fresh and dry germination weight, and all NS treatments improved seed germination and growth development compared to the control. Our findings indicate that NSi had a positive impact on the germination percentage and germination time of melon seedlings under salt stress. This result is in line with a study conducted by Sembada et al. (2023) and Acharya et al. (2024), in which they observed improved germination of tomato (*Solanum lycopersicum*) seeds when subjected to silica nanoparticles.

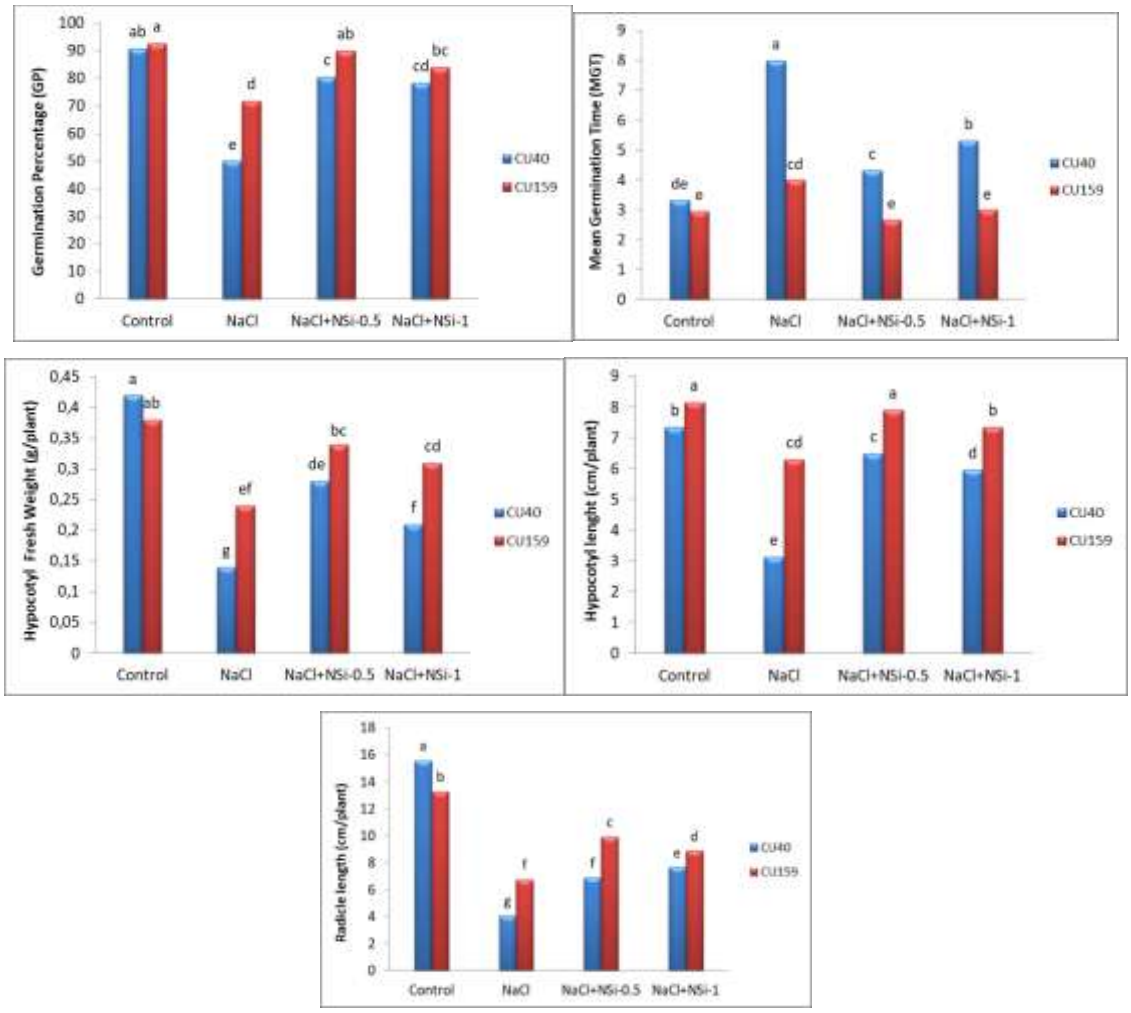

Figure 1. Effects of NSi application on germination parameters under salt stress condition

The melon seedling emergence rate and emergence speed varied depending on salt stress. Under stress conditions, the emergence rate decreased by 47% in the genotype CU40 and by 29% in CU159, compared with the control plants. Conversely, emergence speed increased under stress by 59% in CU40 and by 27% in CU159. NSi applications improved the emergence rate by 21–67% and the emergence speed by 6–29% under stress conditions. While the emergence rate increased, days to emergence decreased following NSi treatments (Figure 2).

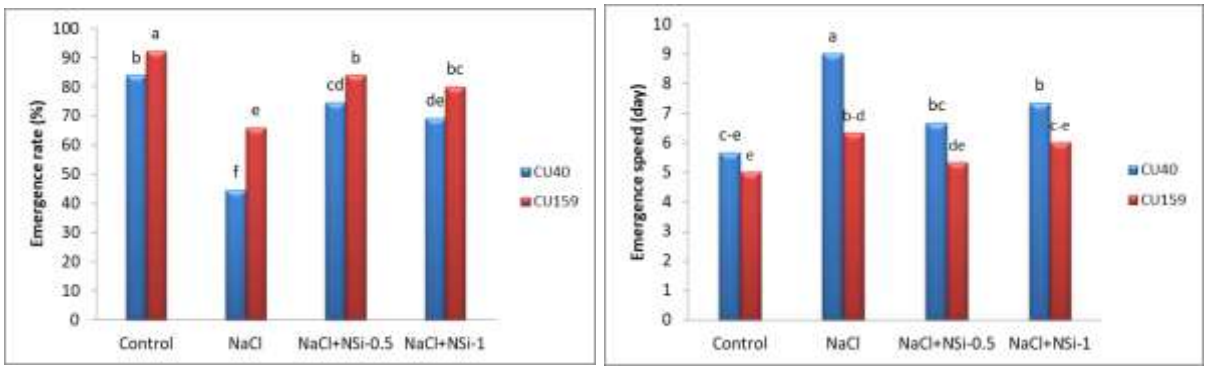

Figure 2. Effects of NSi application on emergence rate (%) and speed (day) under salt stress condition

In the study, where seedling and root fresh/dry weights were also evaluated, seedling fresh and dry weights decreased under salt stress by 55% and 71% in the CU40 genotype, and by 26% and 39% in the CU159 genotype. With NSi applications, these reductions were limited to 32–46% in CU40 and 13–36% in CU159. Regarding root fresh and dry weights, salt stress caused reductions of 76% and 69% in CU40, and 43% and 49% in CU159. Under NSi treatments, the decrease in root fresh and dry weights remained at 34–51% for the CU40 genotype and 22–38% for CU159. Overall, NSi applications provided improvements of 5–176% in seedling and root fresh/dry weight parameters under salt stress conditions (Figure 3).

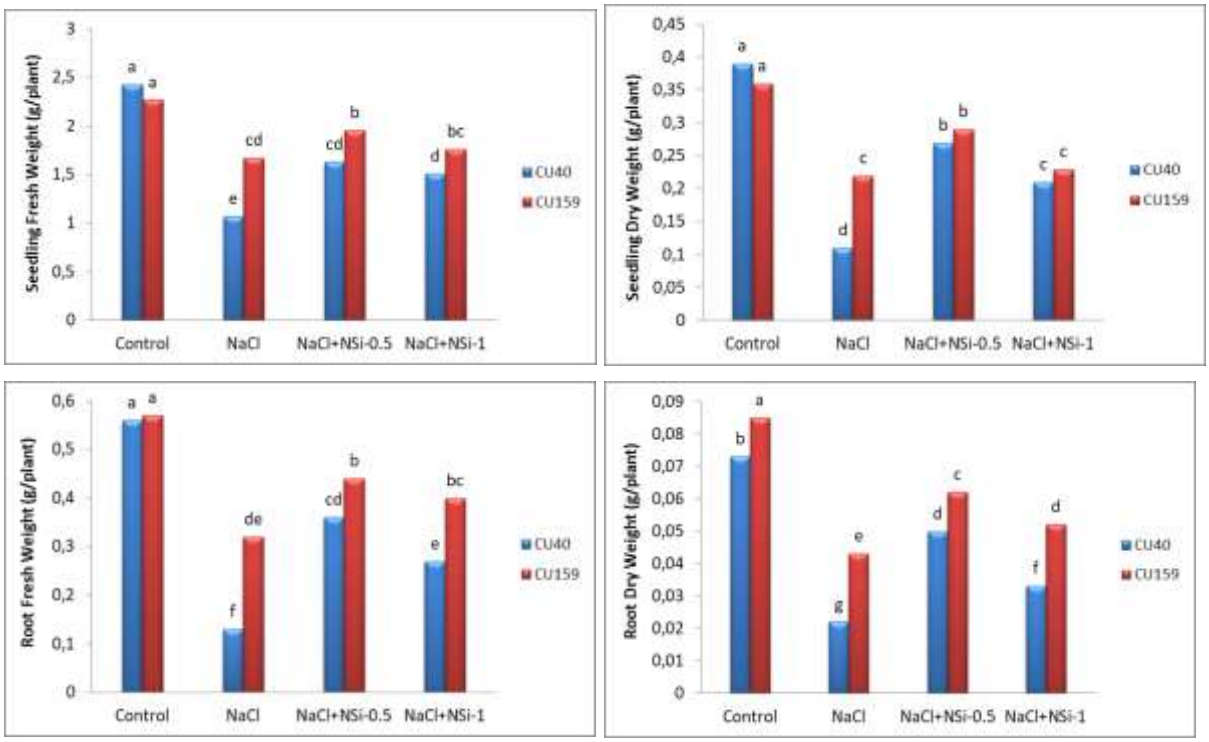

Figure 3. Effects of NSi application on seedling and root fresh and dry weights under salt stress condition

Salt stress reduces plant growth and yield mainly through two mechanisms: the osmotic stress it creates and the toxic effects of excessive ions. These ion imbalances disrupt cellular homeostasis and interfere with the physiological and biochemical processes occurring within the plant (Alsaeedi et al. 2018). Alsaeedi et al. (2018) reported that under salt stress conditions in cucumber, the application of NSi (0, 100, 200, and 300 ppm) enhanced germination parameters and vegetative growth, thereby effectively mitigating the detrimental effects of high Na^+ salinity. Five rates of NSi suspensions (0, 100, 200, 300 and 400 mg L^{-1}) were used to study their effects on seed germination and growth development of cucumber (*Cucumis sativus*). The rate of 200 mg L^{-1} significantly increased final germination%, germination speed, vigor index, and germination index by 28.7, 70.3, 46.7 and 68.8 %, respectively, compared to untreated seeds. However, it reduced the mean germination time by 31.7%. Similarly, 200 mg L^{-1} NSi had the highest fresh and dry weight of germinant. However, all NSi treatments enhanced the seed germination and growth development in comparison to control. Similarly, it was confirmed that the addition of NSi (1 mM SiO2) improved lentil genotypes' germination and early seedling growth after exposure to 100 mM NaCl and stimulated immunity mechanisms against salt toxicity (Sabaghnia and Janmohammadi 2014).

CONCLUSION

Salt stress is considered one of the most critical abiotic factors adversely affecting seed germination, plant growth, and development. In this study conducted on melon, the application of 150 mM NaCl caused reductions in germination and growth parameters compared with the control plants, while germination time and emergence time increased under saline conditions. The application of NSi improved both germination and growth parameters and helped mitigate the reductions in germination and emergence rates caused by salt stress. These results suggest that NSi can be used as an eco-friendly strategy to improve seed germination and plant growth under salt stress conditions.

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DOMATESTE (*Solanum lycopersicum* L.) TUZ STRES KOŞULLARINDA NANO-SİLİSYUM UYGULAMLARININ BİTKİ BÜYÜME, VERİM VE MEYVE KALİTESİ ÜZERİNDEKİ ETKİSİ

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ÖZET

Toprak tuzluluğu, özellikle domates (*Solanum lycopersicum* L.) gibi sebze bitkilerinde büyüme, verim ve kaliteyi olumsuz etkileyen en önemli abiyotik stres faktörlerinden biridir. Bu çalışmada, nano silisyum (NS) uygulamalarının tuz stresi koşullarında yetiştirilen domates bitkilerinin morfolojik, fizyolojik, verim ve meyve kalite parametreleri üzerindeki etkileri araştırılmıştır. Bu amaçla kontrol bitkilerinde tuz düzeyi EC 1.5- 2 dSm^{-1} düzeyinde tutulurken, tuz stresi uygulaması gerçekleştirilen bitkilerde 5 dSm^{-1} düzeyinde tutulmuştur. Nano-Si (N-Si) uygulaması için; 0, 0.5, ve 1 mM olmak üzere 3 farklı konsantrasyon çalışmaya dahil edilmiştir. Stres uygulamasının başlamasından 63 gün sonra ölçüm ve analizler yapılmıştır. Tuz stresi, kontrol bitkilerine oranla bitki yaş ve kuru ağırlığı, gövde boyu, gövde çapı, klorofil içeriği (SPAD), meyve sayısı, meyve ağırlığı ve toplam verimde azalmalara neden olmuştur. Ancak özellikle 0.5 mM NSi uygulaması, bu olumsuz etkileri önemli ölçüde hafifletmiştir. NS uygulanan bitkilerde yaş ve kuru ağırlık, SPAD değeri ve verim parametrelerinde belirgin artışlar gözlenmiştir. Ayrıca NSi uygulamaları, suda çözünebilir kuru madde miktarı (SÇKM) ve Vitamin C içeriğini artırarak meyve kalitesini iyileştirmiştir. Sonuçlar, nano silisyumun tuz stresi koşullarında domatesin toleransını artırarak büyüme ve fizyolojik performansı desteklediğini ve meyve kalitesini koruduğunu göstermiştir.

Anahtar Kelimeler: Abiyotik Stres, Domates, Meyve Kalitesi, Nano Silisyum, Tuz Stresi, Verim

EFFECTS OF NANO-SILICON APPLICATIONS ON GROWTH, YIELD, AND FRUIT QUALITY IN TOMATO (*Solanum lycopersicum* L.) UNDER SALT STRESS CONDITIONS

ABSTRACT

Soil salinity is one of the most critical abiotic stress factors that adversely affect plant growth, yield, and quality, particularly in vegetable crops such as tomato (*Solanum lycopersicum* L.). In this study, the effects of nano-silicon (NS) applications on the morphological, physiological, yield, and fruit quality parameters of tomato plants grown under salt stress conditions were investigated. For this purpose, the electrical conductivity (EC) of the nutrient solution was maintained at 1.5–2 dS m^{-1} in the control plants, while it was adjusted to 5 dS m^{-1} in salt-stressed plants. Nano-silicon was applied at three different concentrations: 0, 0.5, and 1 mM. Measurements and analyses were conducted 63 days after the initiation of stress treatments. Salt stress significantly reduced shoot fresh and dry weight, plant height, stem diameter, chlorophyll content (SPAD), fruit number, fruit weight, and total yield compared to the control plants. However, nano-silicon application, particularly at 0.5 mM, substantially mitigated these adverse effects. Plants treated with NS exhibited notable improvements in shoot biomass, SPAD values, and yield parameters. Moreover, NS treatments enhanced soluble solid content (TSS) and vitamin C levels, thereby improving fruit quality. The results demonstrated that nano-silicon enhances tomato tolerance to salinity by supporting growth and physiological performance while maintaining fruit quality under salt stress conditions.

Keywords: Abiotic Stress, Fruit Quality, Nano-Silicon, Salt Stress, Tomato, Yield

INTRODUCTION

One of the most significant agricultural consequences of climate change is the increasing prevalence of abiotic stress conditions that negatively affect crop production. Abiotic factors not only impair plant growth, yield, and product quality but also contribute to the proliferation of diseases and pests. Among abiotic stressors such as drought, extreme temperatures, flooding, and heavy metals, salt stress is considered one of the most problematic constraints in crop cultivation. Excessive soil salinity reduces the productivity of many agricultural crops and is particularly detrimental to vegetable production, where it can cause substantial yield losses (Atalan and Gökçe, 2021).

Salt stress negatively affects plants by inhibiting germination, growth and development, flowering, and fruit set. High sodium concentrations in saline soils restrict water uptake and nutrient absorption in plants. Water deficiency and nutrient imbalance lead to primary stress responses, including osmotic and ionic stress. These primary stresses subsequently result in oxidative stress, which may further trigger secondary stress responses. Salt stress induces various physiological and molecular alterations, and by limiting photosynthesis, it ultimately causes significant impairments in plant growth and development (Van Zelm et al., 2020; Gong, 2021).

Nanoparticles are small molecular particles ranging from 1 to 100 nm in size and are generally referred to as nanoscale particles (NSPs). They have wide applications in agriculture, including plant growth and development promoters, herbicides, nano-pesticides, and nano-fertilizers. The use of nano-fertilizers in small quantities contributes to fertilizer efficiency and helps reduce soil toxicity resulting from the accumulation of chemical fertilizers and pesticides. Additionally, under abiotic and biotic stress conditions, nanoparticles activate various physiological and biochemical mechanisms that enhance plant tolerance to stress (DeRosa et al., 2010; Siddiqui et al., 2015; Saxena et al., 2016).

Silicon is the second most abundant element in the Earth's crust (28%) after oxygen, and the most abundant element in soils (54%). Although silicon is known as a beneficial or semi-essential element due to its important roles in plants under stress, it does not meet the criteria for essentiality and lacks sufficient evidence confirming its direct involvement in plant metabolism; therefore, it is classified as a non-essential nutrient. Despite not being widely recognized as an essential nutrient, silicon is generally considered a "valuable element" or a "structural element" due to its positive effects on plant growth, physiological and metabolic pathways, cellular structure, and its ability to alleviate a wide range of abiotic and biotic stresses. Numerous studies have confirmed its role in enhancing plant growth, development, and yield under abiotic stress conditions such as salinity, heavy metal toxicity, and drought across various plant species (El-Ramady et al., 2022).

In terms of both production volume and species diversity, the majority of vegetables grown in Türkiye belong to the Solanaceae family. Tomato, which holds substantial global and national importance, is cultivated over large areas and represents one of the most significant vegetable crops used both fresh and for processing. In the present study, the effects of nano-silicon (NS) application on plant growth and fruit quality parameters of tomato were investigated under salt stress conditions (6 dS/m).

MATERIAL AND METHOD

In this study, the tomato cultivar *Android* was used as plant material. Seedlings were transplanted into 24-liter plastic pots filled with a peat:perlite mixture (2:1), with three plants per pot. Plants were irrigated with a standard nutrient solution, and irrigation was managed

based on the ratio of "drainage solution/applied solution" as described by Schröder and Lieth (2002). Drainage levels were monitored daily, and this ratio was maintained at approximately 30% throughout the experiment depending on plant growth.

Salt stress treatments were initiated when plants reached the flowering stage. For this purpose, the electrical conductivity (EC) of the nutrient solution was maintained at 1.5–2 dS m^{-1} for control plants, while it was adjusted to 5 dS m^{-1} for salt-stressed plants using NaCl to achieve the target EC level. For the nano-silicon (NS) treatments, three concentrations 0, 0.5 ($NS_{0.5}$), and 1 (NS_1) mM were included in the experiment. Control plants continued to receive only the standard nutrient solution.

Sixty-three days after the initiation of salt stress, plants were harvested and evaluated for morphological traits (fresh and dry weight, stem diameter, plant height, SPAD readings), yield components, and fruit quality parameters (fruit number, fruit weight, fruit dry matter content, juice pH and EC, titratable acidity, soluble solids content, and vitamin C content).

A randomized complete block factorial design was used in the study. The numerical data obtained were subjected to analysis of variance (ANOVA) using the JMP statistical software package (version 13.0, SAS Institute Inc., USA). Differences among treatments were determined using the Least Significant Difference (LSD) test at the $p < 0.05$ significance level, and statistical groupings were indicated by lettering.

RESULTS AND DISCUSSION

In the study investigating the effectiveness of NS application under salt stress conditions, shoot fresh and dry weights were measured and are presented in Table 1. The highest shoot fresh and dry weight values were recorded in the control plants (2140 and 757.75 g $plant^{-1}$, respectively). Under salt stress, shoot biomass decreased by 44–72% compared with the control. With the $NS_{0.5}$ treatment, this reduction was limited to 12–15%, while in the NS_1 treatment it remained within 22–29%.

The effects of salt and NS treatments on plant height and stem diameter are also shown in Table 1. The greatest plant height and stem diameter were obtained in the control plants, with 248 cm $plant^{-1}$ and 21 mm $plant^{-1}$, respectively. Under salt stress, plant height and stem diameter decreased by 37–49%, whereas with $NS_{0.5}$ these reductions were limited to 12–13%, and to 16–20% with NS_1.

SPAD values decreased by 45% under salt stress relative to the control, while the decrease was only 7% in the $NS_{0.5}$ treatment and 15% in the NS_1 treatment. When comparing salt-stressed plants with those receiving NS treatments, an improvement of 54–70% in SPAD readings was observed (Table 1).

Table 1. The effects of NS application on growth parameters under salt stress

	Shoot Fresh Weight (g/plant)	Shoot Dry Weight (g/plant)	Plant Height (cm/plant)	Stem Diameter (mm/plant)	SPAD
C	2140.00 a	757.75 a	248.00 a	21.83 a	60.55 a
S	1181.00 c	211.47 c	155.33 b	12.51 c	33.24 c
S+$NS_{0.5}$	1882.33 b	640,66 b	219.00 a	19.22 ab	56.59 ab
S+NS_1	1678.33 b	541.43 b	209,33 a	17.43 b	51.47 b

* Means shown with different letters are statistically different within 5% error limits according to the LSD test.

In the study, yield and quality parameters were also evaluated. The highest yield per plant was obtained in the control treatment with 4.48 kg m^{-2}, whereas yield decreased to 1.43 kg m^{-2} under salt stress, 3.16 kg m^{-2} with the $NS_{0.5}$ treatment, and 2.80 kg m^{-2} with the NS-1 treatment. Salt stress caused a 68% reduction in yield compared with the control, while this reduction was limited to 30% with $NS_{0.5}$ and 38% with NS_1 (Figure 1). The highest values for fruit number (315.4 fruits $plant^{-1}$), fruit weight (225.26 g), and fruit dry weight (16.06 g) were also recorded in the control treatment. All of these parameters decreased under salt stress compared with the control plants. The reductions were 60% for fruit number, 55% for fruit weight, and 73% for fruit dry weight. Under salt stress, the $NS_{0.5}$ treatment resulted in only 13–31% reductions in fruit number, fruit weight, and fruit dry weight relative to the control, while in the NS_1 treatment these reductions ranged from 17% to 38%. Overall, NS applications yielded improvements ranging from 76% to 159% compared with salt-stressed plants without NS treatment, with $NS_{0.5}$ emerging as the most effective concentration (Figure 1).

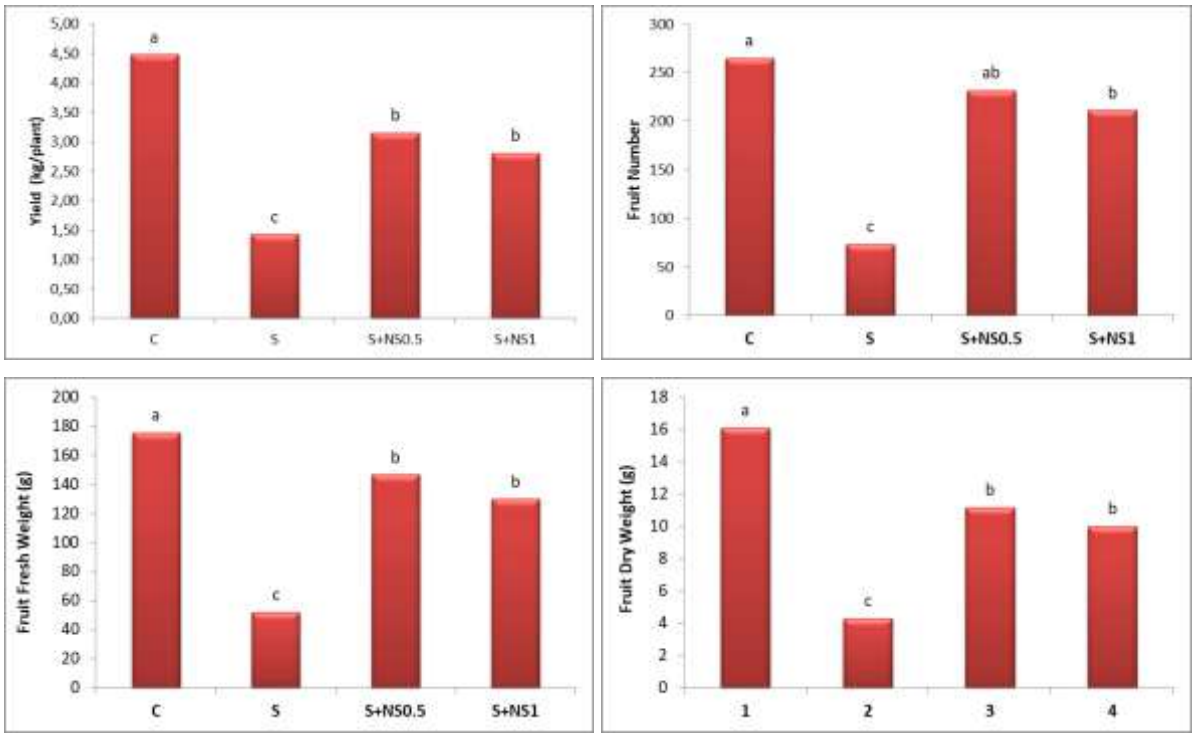

Figure 1. The effects of NS application on yield, fruit number, fresh weight, and dry weight

The effects of salt and NS treatments on soluble solid content (SSC), fruit juice pH, EC, titratable acidity, and vitamin C content were also examined, and the results are presented in Table 3. Accordingly, SSC and vitamin C content increased by 49–117% under salt stress, with the highest values observed in the $NS_{0.5}$ treatment. Regarding fruit juice pH, EC, and acidity, pH decreased by 3–7%, whereas EC and acidity increased by 19–58%. However, the differences among treatments for these parameters were not statistically significant (Figure 2).

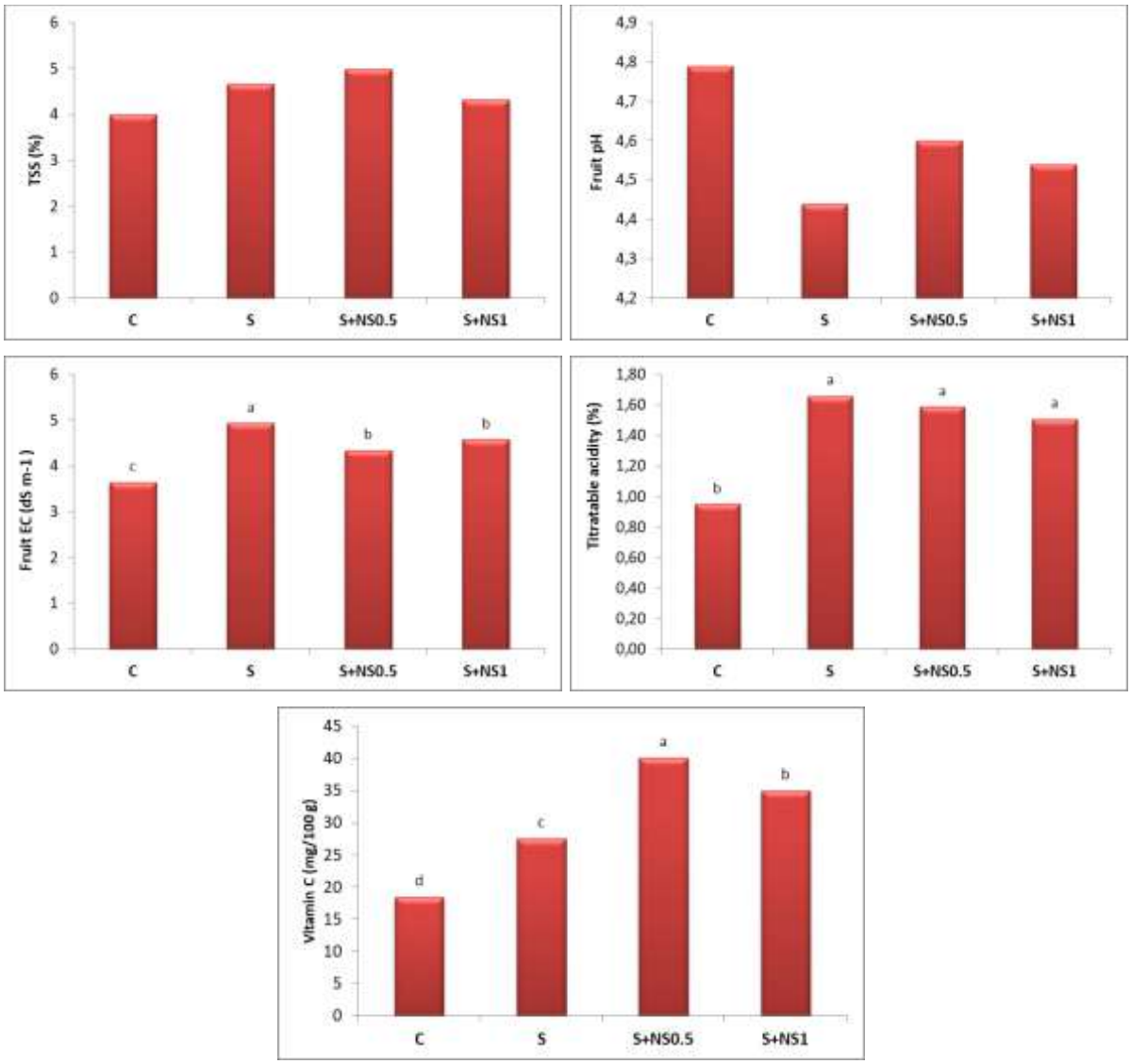

Figure 2. The effects of NS application on fruit soluble solid content (SSC), fruit juice pH, EC, titratable acidity, and vitamin C content

Salt stress adversely affects plant growth and development in parallel with the increasing levels of NaCl and other soluble salts in the soil. As the concentration of salts in the soil solution increases and water potential decreases, the osmotic potential of plant cells is reduced. Consequently, depending on the severity and duration of the salt stress, numerous biological processes including growth, development, germination, cell division, and photosynthesis are negatively affected (Bressan et al., 2008). Salt stress leads to reductions in root and shoot length primarily due to cellular dehydration and subsequent impairments in cell elongation and division (Balasubramaniam et al., 2023). Exposure to salinity also reduces leaf number and leaf area, which in turn results in decreases in fresh and dry biomass (Acosta-Motos et al., 2017). Excessive sodium (Na) accumulation in the soil leads to increased Na^+ uptake and accumulation in plant tissues, disrupting membrane potential and promoting chloride (Cl^-) uptake through electrochemical gradients. Elevated Na^+ concentrations cause osmotic imbalance, membrane damage, and excessive production of reactive oxygen species (ROS), all of which have detrimental effects on various metabolic activities and essential enzymes. As a result, both cell division and cell elongation are adversely affected. Similarly, high Cl^- levels reduce chlorophyll content and damage membrane systems and organelle structures, ultimately

suppressing plant growth (Munns & Tester, 2008; Hao et al., 2021). In the present study, salt stress caused reductions in growth parameters including fresh and dry weight, stem height, and stem diameter ranging from 13% to 72% compared with the control plants. The application of NS substantially mitigated the adverse effects of salt stress, resulting in improvements of 34–156% across these growth parameters. Supporting these findings, Ahmadian et al. (2021) reported that in wheat, salt stress reduced turgor pressure and protoplasmic hydration, leading to declines in photosynthesis and consequently in plant growth and development; however, nano-silicon application enhanced growth parameters under stress conditions. Similarly, Deskoy et al. (2021) noted that NS increased turgor pressure, thereby enhancing water uptake and nutrient acquisition, and ultimately promoting plant growth and development.

Stress conditions lead to chloroplast degradation, destabilization of pigment–protein complexes, chlorophyll loss, and alterations in the quantity and composition of carotenoids (Bayram et al., 2021). Silicon applications have been reported to considerably enhance plant growth and development by increasing total photosynthetic pigment content, photosynthetic rate, chlorophyll concentration, stomatal conductance, transpiration, and intercellular CO_2 concentration (Ndiso et al., 2016; Yaghubi et al., 2016; Avestan et al., 2019). In the present study, salt stress reduced SPAD values by 45% in tomato; however, this reduction was limited to only 6% and 15% in the NS treatments. When compared with salt-stressed plants without NS, improvements of 70% and 54% were achieved, respectively.

Oliveira et al. (2021) reported that under salt stress conditions, increasing salt concentration restricts water and nutrient uptake, resulting in yield losses. In their study on melon, fruit weight, fruit diameter, and yield per plant decreased under different salinity levels (2.5, 5.0, 6.5, and 7.5 dS m^{-1}). Similarly, elevated NaCl concentrations reduced fruit number, fruit weight, and total yield per plant in cucumber, with salt stress at 4 dS m^{-1} causing approximately 60% and 65% reductions in fruit number and total yield, respectively (Brengi et al., 2022). In the present study, NS application resulted in a 27–159% improvement in yield and quality parameters. In a study evaluating plant growth, development, and yield in pepper, salt stress reduced plant growth parameters, total chlorophyll content, fruit number, fruit length, fruit diameter, fruit volume, fruit dry weight, and overall yield, while increasing plant proline and free amino acid content, fruit ascorbic acid, total sugars, total phenolic and flavonoids, and soluble solids (Mostafa et al., 2024). The authors attributed the yield enhancement to improved nutrient uptake and increased photosynthetic activity in leaves due to NS application. Consistent with these findings, studies conducted on tomato (Ebrahimi et al., 2024) and cherry tomato (Islam et al., 2018) reported that NS application significantly improved yield and quality parameters.

CONCLUSION

The results of the study demonstrated that salt-induced drought stress exerted detrimental effects on the morphological, physiological, yield, and quality parameters of tomato. Nano-silicon applications were effective in mitigating the adverse effects of salinity to varying degrees across the evaluated parameters, with the 0.5 mM NS treatment showing the most pronounced positive impact.

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TURBOŞARJ SİSTEMİ RADYAL KOMPRESÖR ÇARK TASARIMI

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ÖZET

Bu çalışmada turboşarj sistemlerinde kullanılan radyal kompresörün ön tasarım metodolojisi ele alınmıştır. İçten yanmalı motorların güç ve verimlilik artışında önemli rol oynayan turboşarj sistemlerinin en kritik bileşeni kompresör çarkıdır ve çark tasarımı, basınç oranı ve izentropik verim gibi performans parametrelerini doğrudan etkilemektedir. Bu nedenle çark tasarımına yönelik doğru bir metodoloji geliştirilmesi, motor performansını artırmak açısından büyük önem taşımaktadır. Bu kapsamda, literatürde yer alan temel prensipler dikkate alınarak tasarım süreci için sistematik bir yaklaşım benimsenmiştir. İlk aşamada kompresörün servis koşulları ve hedeflenen performans isterleri tasarım girdileri olarak tanımlanmış, ardından bu girdilerden hareketle hız üçgenleri ve akışa ilişkin termodinamik parametreler hesaplanmıştır. Hesaplamalarda akışkanlar mekaniği ve termodinamiğin temel denklemleri (süreklilik, momentum, enerji korunumu ve hal denklemleri) ile birlikte izentropik süreçlerde basınç, sıcaklık ve hız arasındaki ilişkiler ve ideal gaz bağıntıları esas alınmıştır. Bu değerler doğrultusunda kanat profili tasarımı için gerekli büyüklükler belirlenmiş ve ön tasarım oluşturulmuştur. Geometri, ANSYS Workbench yazılımındaki Vista CCD modülü kullanılarak hazırlanmış, ardından BladeGen modülünde üç boyutlu çark modeli elde edilmiştir. Bu yaklaşım, hesaplanan parametrelerin geometrik modele doğru bir şekilde aktarılmasını sağlamış, aynı zamanda tasarım üzerinde kolay değişiklik yapılmasına ve farklı konfigürasyonların denenmesine imkân vermiştir. Sonuç olarak, belirlenen performans kriterlerine uygun ve optimize edilebilir bir radyal kompresör geometrisi elde edilmiştir.

Anahtar Kelimeler: Turboşarj, Radyal Kompresör, Çark Tasarımı, Ön Tasarım, Turbo makine, Akışkanlar mekaniği

TURBOCHARGER SYSTEM RADIAL COMPRESSOR IMPELLER DESIGN

ABSTRACT

This study considers the preliminary design methodology for the radial compressor used in turbocharger systems. The compressor impeller, a critical component that plays a significant role in increasing power and efficiency in internal combustion engines, directly influences performance parameters such as pressure ratio and isentropic efficiency through its design. Therefore, proper methodology of the impeller design is crucial for enhancing the engine performance. In this context, a systematic approach was adopted for the design process, taking into account the basic principles in the literature. In the first stage, the compressor's service conditions and targeted performance specifications were defined as design inputs. Then, from these inputs, velocity triangles and the thermodynamic parameters which is related to the flow were calculated. The calculations were performed based on the fundamental equations of fluid mechanics and thermodynamics (continuity, momentum, energy conservation, and equations of state), taking into account the relationships between pressure, temperature, and speed in isentropic processes and ideal gas relations. Necessary blade dimensions to design the blade profile are determined according to these calculated values. Then the preliminary impeller design is obtained. The geometry is created using the Vista CCD module in ANSYS Workbench, followed by a three-dimensional impeller model generated in the BladeGen module. This approach ensured the accurate conversion of calculated parameters to the geometric model, while also allowing for easy design modifications and testing of different configurations. As a result, a radial compressor geometry that meets the desired performance criteria and suitable for optimized was achieved.

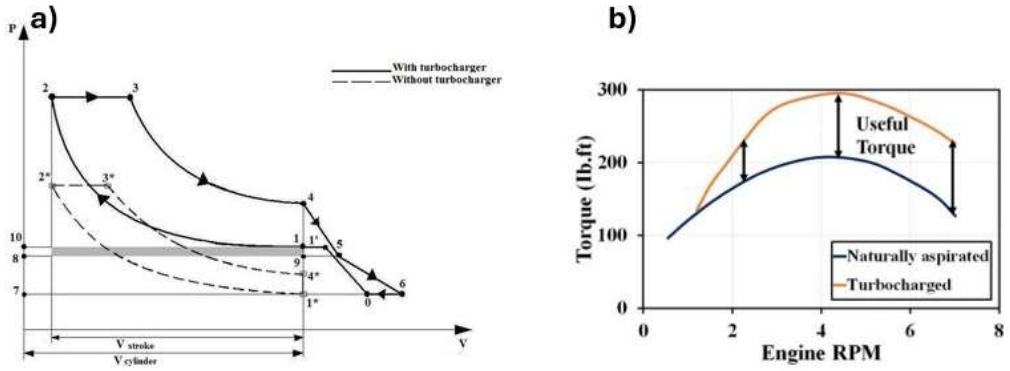
Keywords: Turbocharger, Radial Compressor, Impeller Design, Preliminary Design, Turbomachinery, Fluid Mechanics

1. GİRİŞ

Dünyada iş akışkanı olarak havayla çalışan bir motorun gücünü artırmak amacı üzerinde düşünüldüğünde başta otomobil olmak üzere diğer motor üreten sektörlerde akla ilk gelen yöntemlerden biri motora daha fazla oksijen dolayısıyla hava göndermek olmuştur. Bu işlevi yerine getirme kabiliyetine sahip olan sistemlerden biri turboşarj sistemleridir [1,2]. Her ne kadar günümüzde elektrikli motorlar turboşarj sisteminin kullanıldığı motorların yerini almaya başladıysa da dünyadaki fosil enerji kaynaklarının miktarının yenilenebilir enerji miktarından fazlalığı düşünüldüğünde elektrifikasyona geçiş sadece başlangıç aşamasında kalmakta ve mecburi olarak uzun yıllar boyunca yanma reaksiyonlu dolayısıyla turboşarj sistemli motorlar kullanılacağı uzmanlar tarafından öngörülmektedir [3,4]. Ayrıca gelecekte yaygınlaşacağı düşünülen hidrojen yakıtlı motorlarda da turboşarj sisteminin kullanılabileceği öngörülmektedir [5]. Bu sebeplerden dolayı günümüzde hala turboşarj sistemlerinin geliştirilmesi için şirketler yatırımlar yapmakta ve AR-GE çalışmalarını sürdürmektedirler. Şirketler bu çalışmalarını ticari bir sır olarak sakladıkları için turboşarj tasarımları hakkındaki bilgimiz literatürdeki az sayıda araştırma ile sınırlıdır. Bu araştırmaların çoğunluğu turboşarj sistemlerindeki çeşitli parçaların sonlu hacimler analizleri ile optimizasyonlarını içermektedir [6,7]. Bu bildiride de turboşarj sistemi incelenmiş ve bu sistemdeki en önemli parçalardan biri olan radyal kompresörün ön tasarım metodolojisi anlatılmıştır.

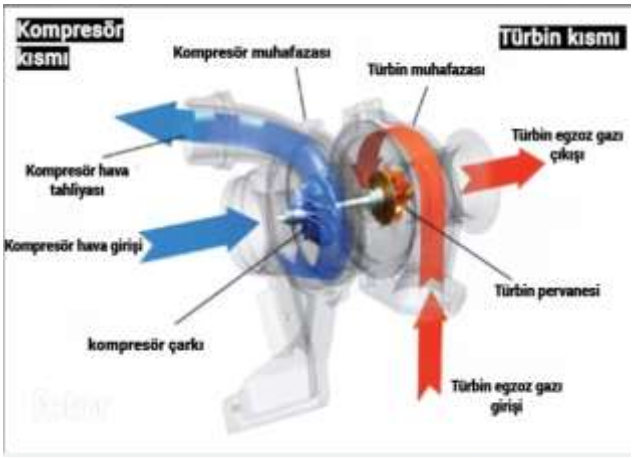
İçten yanmalı motorların verimini artırmak için kullanılan yöntemler arasında silindir hacmini büyütmek, strok boyunu artırmak, devir sayısını yükseltmek, silindir sayısını artırmak ve ortalama indike basıncı yükseltmek sayılabilir. Bu yöntemlerin birçoğu motorun yapısal özelliklerine bağlı olduğundan her zaman uygulanabilir değildir. Turboşarj sistemi ise bu yollar içinde ortalama indike basıncı artırarak motorun daha yüksek güç ve verim elde etmesini sağlar. İndike basınç artarsa elde edilecek iş dolayısıyla motor gücüde artacaktır. Basıncı artırmak için motor konstrüksiyonunda herhangi bir parametreyi değiştirmek gerekmez bunun için motora uygun turboşarj sistemi eklenmesi yeterlidir [2].

Turboşarj, motora basınçlı ve soğutulmuş hava göndererek silindir başına giren hava kütlesini artırır. Bu, yanma sırasında daha yüksek basınç üretir. Yanma basınç eğrisinin ortalaması olan indike basınç yükseldiği için motorun indike gücü artar. Şekil 1a'da bir dizel motorun P–V diyagramında turboşarj sisteminin etkisi görülmektedir [8]. Diyagramda çevrimin kapalı alanı işi temsil ettiğinden, turboşarjlı durumda alanın büyümesi motorun ürettiği işin arttığını ve dolayısıyla turboşarj sisteminin motor gücünü artırmadaki etkisini açıkça ortaya koymaktadır. Şekil 1b'de görüldüğü üzere turboşarjlı motor, doğal emişli motora göre daha yüksek tork üretmektedir [9]. Özellikle düşük ve orta devirlerde belirginleşen bu fark, silindire daha fazla hava ve yakıt gönderilmesiyle yanma veriminin artmasından kaynaklanmaktadır. Böylece motorun hem torku hem de güç eğrisi daha geniş bir devir aralığında yüksek seviyede kalmakta, bu da turboşarj sisteminin performans üzerindeki etkisini açıkça göstermektedir.



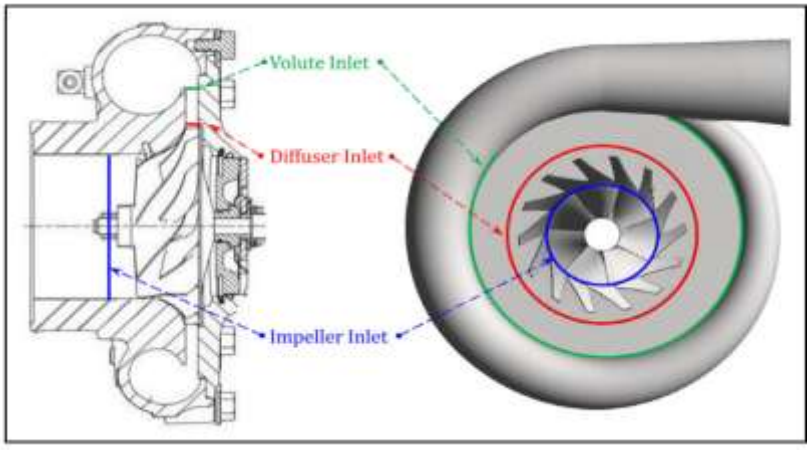
Şekil 1. a) Turboşarj sisteminin bir dizel motorun termodinamik çevrimi üzerindeki etkisi [8].
b) Turboşarj sisteminin doğal emişli motorlara göre sağladığı tork artışı [9].

Turboşarj sistemi temelde üç ana bölümden oluşur: egzoz enerjisini işe çeviren türbin, havayı basınçlandıran kompresör ve ikisini bağlayan merkez bölüm (şaft, yataklama, yağlama) (Şekil 2). Bu yüzden kompresör ve türbinin verimleri turboşarjın performansını belirler.



Şekil 2. Turboşarj sisteminin kısımları ve işleyişi [10].

Radyal kompresörde akışkan, çarkta hız kazanarak kinetik enerjiye dönüşür; difüzör ve volütte ise bu hız azalırken kinetik enerji statik basınca çevrilir (Bu kısımlar şekil 3 'te gösterilmiştir.). Böylece girişten çıkışa doğru akışkanın enerjisi düzenli şekilde basınç artışına dönüştürülür.



Şekil 3. Kompresörün çark, difüzör ve sarmal kısımların girişleri [11].

Turboşarj sistemindeki kompresörün kısmının en önemli parçası çark kısmıdır. Bu çarkın tasarımı, basınç oranı ve izentropik verim olmak üzere kompresörün genel performans karakteristiklerini doğrudan etkiler. Bu yüzden kompresörden istenilen etkiyi almak için çark tasarımı büyük bir önem arz etmektedir.

Literatürde kompresör çarkının tasarımı ile alakalı çalışmalar incelendiğinde Kong vd. [7] çalışmalarında santrifüj kompresör çarkları için bir tasarım metodolojisi sunmuştur. Chun vd. [12] yaptığı çalışmada, egzoz gazlarıyla çalışan bir Wärtsilä 20V34SG motoru için off-design turboşarj modellemesi geliştirilmiştir. Çalışmada önce GT-Power yazılımında 1D motor modeli oluşturulmuş, ardından turboşarj modeli EES yazılımında kalibre edilmiştir. Bourabia vd. [6] çalışmalarında, santrifüj kompresörler için 1D mean-line model ile kayıp modellerini evrimsel optimizasyon teknikleri (GA, NSGA-II) ile birleştirerek ön tasarım optimizasyonu gerçekleştirmiş, böylece farklı performans hedeflerini aynı anda karşılayan hızlı ve otomatik bir tasarım yaklaşımı önermişlerdir. Bu yönüyle, klasik 1D ön tasarıma dayalı yöntemlerden ayrılmaktadır. Xu ve Amano [13] çalışmalarında, motor verimliliğini artırmak amacıyla turboşarjın kompresör ve türbinini birlikte ele alan bütünleşik bir tasarım yaklaşımı geliştirmişlerdir.

Bu çalışmada ise literatürde sunulan farklı yaklaşımlardan faydalanılarak, özellikle turboşarj kompresör çarkının ön tasarım metodolojisi üzerine odaklanılmıştır. Bu çalışmada, temel termodinamik ve akışkanlar mekaniği denklemleri üzerinden sistematik bir ön tasarım yaklaşımı izlenmiş, hız üçgenleri ve performans parametreleri esas alınarak bir turboşarj kompresör çarkı için hesaplamalar gerçekleştirilmiştir.

2. MATERYAL VE YÖNTEM

Radyal kompresörler oldukça karmaşık geometrik özelliklere sahip olup, parametrelerin farklı kombinasyonları milyonlarca olasılık ortaya çıkarabilmektedir. Bu nedenle tasarım sürecinde izlenecek adımların önceden belirlenmesi, yani sistematik bir algoritmanın oluşturulması gereklidir. İlk aşamada turboşarj kompresörleri için genel karakteristik değerler belirlenir; tasarımdan beklenen isterler ile kompresörün çalışacağı servis koşulları netleştirilmelidir. Ardından hedeflenen sıkıştırma oranı ve verimlilik değerleri doğrultusunda teorik bir hesaplama yapılır. Bu hesaplamalar neticesinde bazı parametrelere ait değerler elde edilmektedir. Elde edilen bu değerler kullanılarak ANSYS programındaki modüllerle çark geometrisi elde edilmiş olur.

Başlangıçtaki kanat profili oluşturulmadan önce giriş ve çıkış bölgelerindeki hız üçgenlerinin belirlenmesi gerekmektedir. Hız üçgenlerinden elde edilen bağıntılar, akışkanlar mekaniği ve termodinamiğin temel yasaları ile birlikte kullanılarak çark tasarımına ulaşılmaktadır. Gaz akışının hâkim olduğu bu tür sistemlerde süreklilik denklemi, enerjinin korunumu, momentum denklemleri ve gazların hâl ilişkileri hesaplamaların temelini oluşturmaktadır. Ayrıca, izantropik süreçlerde basınç, sıcaklık ve hız arasındaki ilişkiler, ideal gaz denklemi ve sıkıştırılabilirlik faktörü gibi bağıntılar da tasarım sürecinde önemli rol oynamaktadır.

Bu çalışmada, kompresör tasarımına yönelik hesaplamalarda kullanılan denklemler 1'den 25'e kadar verilmiştir:

$$\frac{T_0}{T_s} = 1 + \frac{\gamma-1}{2} M^2 \quad (1)$$

$$\frac{T_0}{T_s} = \left(\frac{P_0}{P_s}\right)^{\frac{\gamma-1}{\gamma}} \quad (2)$$

$$\frac{P_0}{P_s} = \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}} \quad (3)$$

$$H_{ad} = C_p(T_{02} - T_{01}) = C_p \left[\left(\frac{P_{02}}{P_{01}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] = \frac{\gamma R T_{01}}{\gamma-1}\left[\left(\frac{P_{02}}{P_{01}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \quad (4)$$

$$\frac{\dot{m}}{A} = \sqrt{\frac{\gamma}{R}} \frac{P}{\sqrt{T}} \frac{M}{\left(1+\frac{\gamma-1}{2}M^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}} \quad (5)$$

$$T_0 = T_s + \frac{V^2}{2C_p} \quad (6)$$

$$P_0 = P_s + \rho \frac{V^2}{2g} \quad (7)$$

$$V_1^2 = V_{\theta 1}^2 + V_{m1}^2 \quad (8)$$

$$V_2^2 = V_{\theta 2}^2 + V_{m2}^2 \quad (9)$$

$$W_1^2 = (U_1 - V_{\theta 1})^2 + V_{m1} \quad (10)$$

$$W_2^2 = (U_2 - V_{\theta 2})^2 + V_{m2} \quad (11)$$

$$W = \sqrt{(V_\theta - U)^2 + V_m^2} \quad (12)$$

$$U = 2\pi r N \quad (13)$$

$$i = \beta_b - \beta \quad (14)$$

$$V_{\theta 2} = U_2 + V_{m2} \tan \beta_{2b} - V_{slip} \quad (15)$$

$$V_{slip} = U_2(1 - \sigma) \quad (16)$$

$$\eta_{rotor} = \frac{PR^{\frac{\gamma-1}{\gamma}} - 1}{TR - 1} \quad (17)$$

$$\sigma = \frac{V_{\theta 2}}{U_2} \quad (18)$$

$$\sigma' = 1 - \frac{0{,}855\pi^2}{z_s} \frac{V_{m2}}{U_2} \quad (19)$$

$$1 - \sigma = \frac{V_{\theta 2}}{U_2}\left(\frac{1}{\sigma'} - 1\right) \quad (20)$$

$$\frac{\sigma'}{1-\sigma'} = \frac{\frac{V_{m2}}{U_2}\tan \beta_2 + \sigma}{1-\sigma} \quad (21)$$

$$\mu = \sigma \frac{\lambda}{\lambda - \tan \beta_2} \quad (22)$$

$$\lambda = \frac{V_{\theta 2}}{V_{m2}} = \text{Döngü parametresi} \quad (23)$$

$$H_{ad} = \frac{1}{2g}[(V_1^2 - V_2^2) + (U_1^2 - U_2^2) + (W_1^2 - W_2^2)] \quad (24)$$

$$\frac{P_{02}}{P_{01}} = \left[\frac{\gamma-1}{\gamma R T_{01}}(U_1 V_{\theta 1} - U_2 V_{\theta 2}) + 1\right]^{\frac{\gamma}{\gamma-1}} \quad (25)$$

Bu denklemler ile geometrinin oluşturulması için gerekli değerlerin hesaplamasına geçilmeden önce bazı tasarım girdileri belirlenmelidir. Bu girdiler radyal kompresörün kullanılacağı yer ve servis şartlarına göre değişmektedir. Bu çalışma için kullanılan parametreler Tablo 1'de verilmiştir.

Tablo 1. Tasarım girdileri ve gereksinimleri

Parametre	**Değer**
Devir Sayısı	1600 dev/s
Giriş Toplam Basıncı	101325 Pa
Giriş Toplam Sıcaklığı	288,15 K
Ana Kanat Sayısı (main blade)	7
Ayırıcı kanat sayısı (splitter blade)	7
Göbek Çapı	0,018 m
Uç Çapı	0,071 m
Çıkış çapı	0,088m
Çark Çıkışı Kanat Genişliği	0,00774m
Kütlesel Debi	0,65 ± 0,01 kg/s
Toplam Basınç Oranı	3 ± 0,05
İzentropik Verim	≥ 0,85

Belirlenen parametreler ile hesaplamalara geçilmiştir. Hesaplamalar neticesinde elde edilen parametreler giriş ve çıkış koşullarına göre Tablo 2'de gösterilmiştir.

Tablo 2. Hesaplanan giriş ve çıkış değerleri

Parametre	**Giriş**	**Çıkış**
P	86,459 kPa	184,358 kPa
P_0	101,235 kPa	303,975 kPa
T	275,26 K	358,15 K
T_0	288,15 K	413,15 K
ρ	1,09 kg/m^3	1,76 kg/m^3
V_m	160,95 m/s	172,87 m/s
V	160,95 m/s	332,5 m/s
M	0,483	0,88

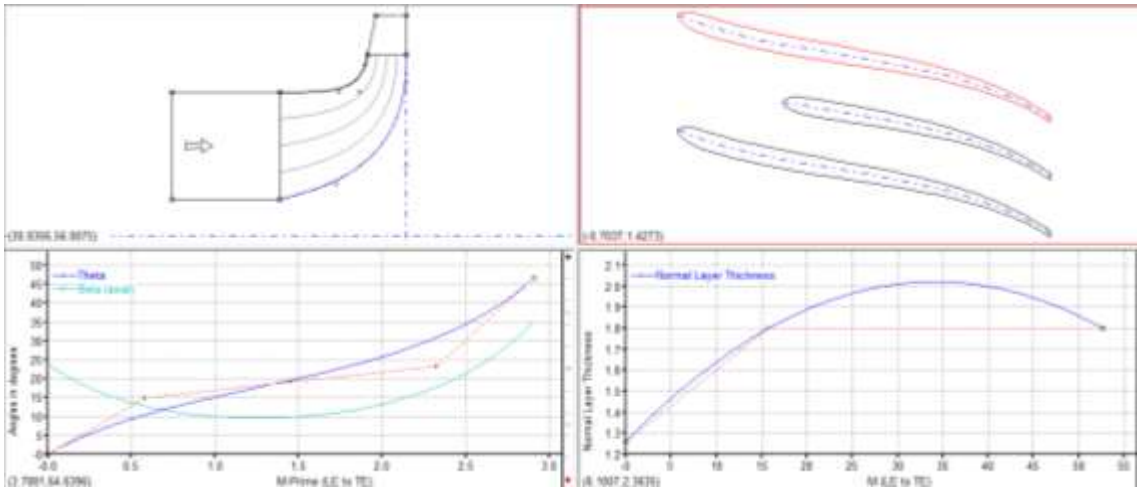
Hesaplamalar neticesinde elde edilen kanat açışı, verimlilik ve hız üçgenlerine ait parametreler Tablo 3'te gösterilmiştir.

Tablo 3. Hesaplamalar neticesinde elde edilen çark hız, açı ve verimlilik değerleri

Parametre	Değeri
U_{1t}	356,885 m/s
U_{1h}	90,478m/s
W_h	184,64 m/s
W_t	391,499 m/s
β_{1h}	29,34°
β_{1t}	65,72°
U_2	442,336 m/s
β_2	−21,207°
η_{rotor}	0,85

3. BULGULAR

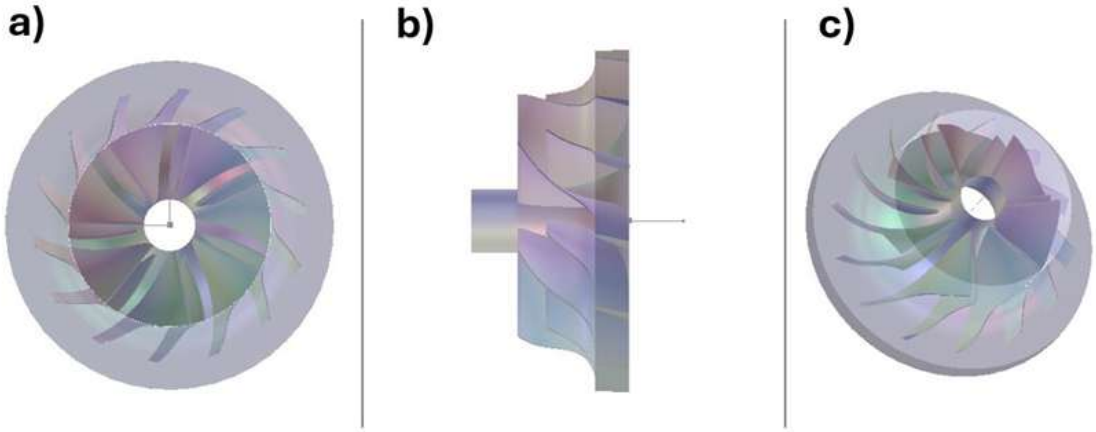
Belirlenen bu değerler kullanılarak öncelikle Vista CCD modülü aracılığıyla bir ön tasarım oluşturulmuş, ardından bu tasarım BladeGen modülüne aktarılmıştır.



Şekil 4. ANSYS BladeGen 2D bıçak profili ve tasarım grafikleri

ANSYS BladeGen modülü, hesaplanan değerler doğrultusunda geometriyi hızlı ve doğru bir şekilde oluşturmaya olanak sağlamakta, ayrıca tasarım üzerinde kolayca değişiklik yaparak farklı varyasyonların denenmesine imkan vermektedir. ANSYS BladeGen modülünde hesaplamalar neticesinde elde edilen ilk tasarım parametreleri şekil 4'te grafikler halinde gösterilmektedir. Bu arayüzü üzerinden çark bıçak kalınlıkları ve açıları, CFX analizleri yapılarak elde edilen sonuçlara göre kolaylıklar değiştirilebilir/optimize edilebilir.

BladeGen ortamında üç boyutlu olarak elde edilen çark geometrisi şekil 5'te verilmiştir.



Şekil 5. Elde edilen radyal kompresör çark modeli

4. TARTIŞMA

Bu çalışmada elde edilen sonuçlar, literatürde yer alan benzer çalışmalar ile karşılaştırıldığında uyumlu bir eğilim göstermektedir. Kong vd. tarafından geliştirilen entegre tasarım prosedürü [7] ve Bourabia vd. tarafından sunulan optimizasyon tabanlı yöntem [6], tasarım sürecini hızlandırmayı ve tasarımcı bağımlılığını azaltmayı amaçlamaktadır. Bu çalışmada ise daha klasik bir yaklaşımla hız üçgenleri ve temel termodinamik/akışkanlar mekaniği denklemleri kullanılarak yapılan ön tasarım, elde edilen geometrinin performans kriterlerini sağlayabildiğini ortaya koymuştur. Böylece, literatürdeki ileri optimizasyon ve deneysel doğrulama temelli yöntemlerden farklı olarak, klasik ön tasarım metodolojisinin pratik uygulanabilirliği ve doğruluğu vurgulanmıştır.

Sonuçların özellikle izentropik verim ve basınç oranı açısından hedef değerleri karşılaması, yöntemin geçerliliğini desteklemektedir. Ayrıca, ANSYS Vista CCD ve BladeGen modülleri ile hesaplanan parametrelerin hızlı bir şekilde üç boyutlu geometriye aktarılabilmesi, tasarım sürecinin esnekliğini ve uygulanabilirliğini göstermektedir. Bu yönüyle çalışma, literatüre klasik hesaplama yöntemlerinin güncel yazılım araçlarıyla bütünleştirilerek kullanılabileceğini göstermesi bakımından katkı sağlamaktadır.

Bununla birlikte, tasarlanan geometriye yönelik CFD analizleri ve deneysel doğrulamalar ilerleyen çalışmalarda gerçekleştirilerek bulguların daha geniş kapsamlı olarak değerlendirilmesi planlanabilir. Bu sayede, elde edilen ön tasarımın gerçek çalışma koşullarındaki performansı da net bir şekilde ortaya konabilecektir.

5. SONUÇLAR

Bu çalışmada, turboşarj sistemlerinde kullanılan radyal kompresör için ön tasarım metodolojisi ortaya konulmuştur. Öncelikle kompresörün servis koşulları ve hedeflenen performans parametreleri tanımlanmış, ardından hız üçgenleri ve temel termodinamik/akışkanlar mekaniği denklemleri kullanılarak hesaplamalar gerçekleştirilmiştir. Elde edilen değerler doğrultusunda Vista CCD modülü ile ön tasarım yapılmış ve BladeGen ortamında üç boyutlu çark geometrisi elde edilmiştir. Çalışmanın sonucunda:

- Hesaplanan parametreler ile elde edilen çark geometrisinin hedeflenen basınç oranı ($3 \pm 0{,}05$) ve izentropik verim ($\geq 0{,}85$) değerlerini sağlayabilecek bir ön tasarıma ulaşılmıştır.

- Klasik ön tasarım hesaplarının, modern yazılım araçları ile bütünleştirilerek kullanılmasının hızlı, doğru ve esnek bir tasarım süreci sunduğu ortaya konmuştur.
- Elde edilen geometri, farklı konfigürasyonların denenmesine ve sonraki aşamalarda CFD analizleri ve optimizasyon çalışmaları ile daha ileri seviyede geliştirilmesine uygundur.
- Dolayısıyla bu çalışma, turboşarj sistemlerinde kullanılan radyal kompresörlerin ön tasarım sürecine yönelik uygulanabilir, sistematik ve optimize edilebilir bir yaklaşım sunmaktadır.

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ADVANCED KINETIC MODELING OF BARK PYROLYSIS USING DISTRIBUTED ACTIVATION ENERGY MODELS

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SUMMARY

Accurate kinetic modeling is essential for optimizing biomass pyrolysis processes such as slow, intermediate, and fast pyrolysis. Traditional first-order kinetic models often fail to capture the complex, multi-reaction nature of lignocellulosic decomposition. In this study, the pyrolysis behaviour of oak bark was investigated using thermogravimetric analysis (TGA) at heating rates of 10, 15, and 20 K/min, following guidelines of International Confederation for Thermal Analysis and Calorimetry (ICTAC 2014). To represent the multistep kinetics, a total of 6 distributed activation energy models (DAEM) were tested, including 2 and 3 Gaussian distributions and a 2-Weibull distribution-based multiple-heating rate models. The 3-Gaussian multiple heating rate DAEM achieved the best fit (R^2 = 0.9922), effectively resolving overlapping thermal events. The Weibull distribution-based model with multiple heating rates also performed well (R^2 = 0.9905), better capturing asymmetric degradation patterns. Validation was carried out using the isoconversional Friedman method, which revealed significant variation in activation energies across the conversion range confirming the distributed kinetic nature of the system. Two primary activation energy regions were identified: First 100 kJ/mol (initial devolatilization) and later 152 kJ/mol (mid-stage decomposition). The findings demonstrate that distributed models significantly outperform traditional first-order approaches for pyrolysis kinetics and provide more realistic representations of thermal behavior of bark. This work supports the thermochemical valorization of barks and highlights the importance of advanced kinetic modeling in waste biomass conversion research.

INTRODUCTION

Pyrolysis is an important thermochemical process to produce biochars and bio-oils from renewable sources such as waste lignocelulosic biomass. The pyrolysis reactions of biomass are often complex and include several overlapping steps due to the heterogeneous chemical composition of biomass. The kinetics of biomass pyrolysis is usually described by a first step degradation kinetics with a single activation energy which is a good approximation but may not explain the kinetics of thermal degradation. Alternatively, the thermal degradation reactions may be modelled by a several parallel first-order or n-th order reactions with variable activation energies (Cai et al., 2014)**.** The activation energies may be modelled by a Gaussian distribution or alternative distribution functions such as Weibull distribution to capture the intrinsic differences between the activation energies of biomass components such as polysaccharides (cellulose and hemicelluloses) and lignin (Yang et al. 2024). The apparent activation energies of biomass may be determined by using a single heating rate or by employing multiple heating rates which is an improvement of the single-heating rate based kinetic analysis. The objectives of this study are to characterize the pyrolysis behavior of oak bark, to evaluate the performance of advanced kinetic modeling approaches by testing a total of 6 distributed activation energy models (DAEM), and to assess the advantages of distributed models over traditional first-order kinetics in describing bark pyrolysis.

RESEARCH AND FINDINGS

A total of 100 g bark samples of Kasnak oak (*Quercus vulcanica*) were obtained from Isparta, Turkey, reduced to 250-420 µm particle size and oven-dried at 60 ºC for 1h and stored in air-tight bags before thermogravimetric analyses. The ash, lignin, suberin, and polysaccharide contents of the analyzed material was 15%, 22%, 4%, and 35%, respectively based on oven-dry weight. Thermogravimetric analysis (TGA) of oak bark samples was carried out following ICTAC 2014 kinetic guidelines (Vyazovkin et al. 2014). A total of 5-7 mg dried and milled bark samples were heated under an inert atmosphere between 25 ºC and 800 ºC using a dynamic heating program at three heating rates (10, 15, and 20 K/min) to generate a reliable single and multi-heating-rate dataset for kinetic analysis. Kinetic modeling was performed by applying 6 distributed activation energy models to represent the multistep nature of oak bark pyrolysis. The tested models included two- and three-Gaussian DAEM formulations as well as a two-Weibull distribution–based model, allowing comparison between symmetric (Gaussian) and asymmetric (Weibull) energy-distribution functions (**Table 1**). Each model was globally fitted to the TG/DTG data from all three heating rates to resolve overlapping decomposition events and estimate distributed activation energy profiles. Kinetic parameters were optimized using standard nonlinear regression methods.

Table 1. Distributed activation energy models tested in this study

Daem models	Abbreviation	Heating rate (K/min)	Number of pseudocomponents	Distribution function
Model 1	M1	10	1	Gaussian
Model 2	M2	10	2	Gaussian
Model 3	M3	10	3	Gaussian
Model 4	M4	10, 15, 20	3	Gaussian
Model 5	M5	10, 15, 20	2	Gaussian
Model 6	M6	10, 15, 20	2	Weibull

Model performance was evaluated using goodness-of-fit statistics (R^2). To validate the distributed kinetic behavior, the isoconversional Friedman method was applied independently (Arenas et al. 2019).

The thermal decomposition profile of the tested biomass is shown in **Fig 1**. As expected, bark did not show a homogeneous thermal decomposition pattern. The decomposition rate was fast between the temperatures approximately 200 ºC and 400 ºC and gradually become slower until 700 ºC and increased again between 700 ºC and 750 ºC. The first decomposition region possibly corresponds to the decomposition of polysaccharides, and second decomposition region corresponds to the degradation of lignin and suberin. The final region possibly occurs by the degradation of char produced in the previous steps. This decomposition pattern agrees with previous publications on the thermal decomposition of lignocellulosic wastes (Chen et al. 2015; Fetisova et al. 2023).

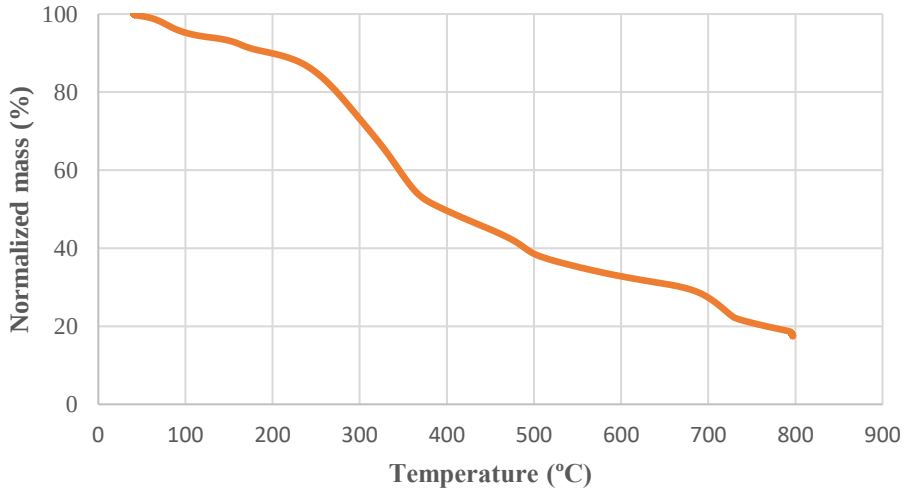

Fig 1. Thermal decomposition of *Q. vulcanica* bark under dynamic heating (Representative curve at heating rate=10 °C/min)

The result of the kinetic modelling is shown in **Table 2**. The DAEM methods distinguished 2 or 3 thermal degradation regions with activation energies approximately 100, 150, and 300 kJ/mol which supports our previous interpretation of the thermal degradation.

Table 2. Activation energies and correlation coefficients of the tested kinetic models

Daem models	Abbreviation	Heating rate (K/min)	Number of pseudocomponents	Ea (kJ/mol)	R^2
Model 1	M1	10	1	185	0.968
Model 2	M2	10	2	158 268	0.997
Model 3	M3	10	3	170 225 289	0.997
Model 4	M4	10, 15, 20	3	100 152 290	0.992
Model 5	M5	10, 15, 20	2	100 152	0.992
Model 6	M6	10, 15, 20	2	101 138	0.990

The single-heating rate-based models seem to capture well the second and the third regions, while the multiple-heating rate-based models captured all three thermal decomposition regions with the first two regions being the principal thermal decomposition regions. Multiple heating rates fitting allows for simultaneous optimization of kinetic parameters in different heating rates. The results of multiple heating rates provide more reliable kinetic data because it removes the compensation between frequency factor and apparent activation energy caused by fitting only a single heating rate. Also, it is physically meaningful because the activation energies obtained are fixed independent of heating rate. It reduces overfitting and allows for prediction of activation energies in different heating rates. On the other hand, it takes a much higher time to compute the kinetic parameters because the fitting is more complex. To further improve the results of DAEM models, Weibull distribution was also tested which resulted in a good fitting (R^2=0.99). The Weibull distribution-based DAEM is considered a more reliable model because it captures the asymmetric thermal degradation of biomass components such as lignin. After employing DAEM-based kinetic analysis, the results were validated using the isoconversional Friedman method (**Fig 3**). The Friedman analysis showed a non-constant activation energy supporting the use of DAEM to study multi-step or complex reaction mechanisms.

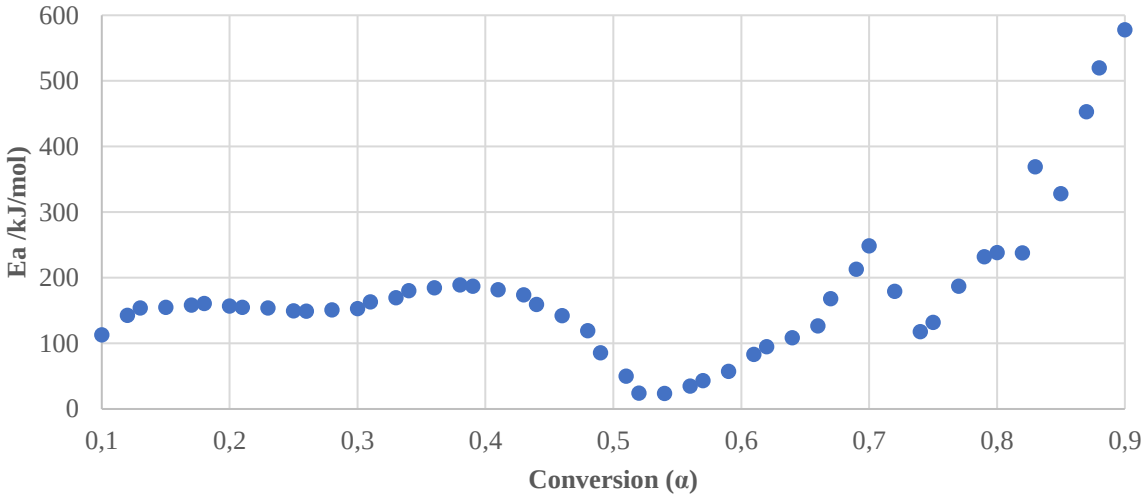

Fig. 3. Application of isoconversional Friedman method for validation of DAEM

CONCLUSION

The results of this study show that the thermal decomposition of *Quercus vulcanica* bark proceeds into two major steps with higher and lower activation energies, possibly reflecting faster and slower decomposing biomass fractions. All DAEM models with Gaussian and Weibull distributions have excellent R^2 (>0.99) values except for single heating 1-pseudocomponent model. The 2-pseudocomponent Weibull-distribution-based multi-heating model resulted in the best results considering the asymmetric degradation pattern of biomass components. The DAEM results were validated by isoconversional Friedman method.

Two primary activation energy regions were identified: First approximately at 100 kJ/mol (initial devolatilization) and later at 152 kJ/mol (mid-stage decomposition). The findings demonstrate that distributed models significantly outperform traditional single activation energy-based models for pyrolysis kinetics and provide more realistic representations of thermal behavior of oak bark. This work supports the thermochemical valorization of lignocellulosic wastes and highlights the importance of advanced kinetic modeling in waste biomass conversion research.

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ENERJİ VE SU SÜRDÜRÜLEBİLİRLİĞİ BAĞLAMINDA FOTOVOLTAİK TERS OZMOS VE DENİZ SUYU ISI POMPASI SİSTEMLERİNİN ENTEGRE DEĞERLENDİRMESİ: KUZEY KIBRIS TÜRK CUMHURİYETİ VAKA ÇALIŞMASI

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ÖZET

Küçük ada devletleri, enerji ve su temini konusunda dışa bağımlılık, fosil yakıtlara dayalı yüksek maliyetler ve iklim değişikliğinin getirdiği zorluklarla karşı karşıyadır. Bu durum, enerji ve su güvenliğinin sürdürülebilir biçimde sağlanabilmesi için yenilikçi yaklaşımların geliştirilmesini zorunlu kılmaktadır. Bu çalışmada, enerji ve su güvenliğini artırmak amacıyla fotovoltaik (PV) panellerle desteklenen ters ozmos (RO) deniz suyu arıtma ve deniz suyu kaynaklı ısı pompası (SWHP) sistemlerinin entegrasyonu, Kuzey Kıbrıs Türk Cumhuriyeti (KKTC) özelinde bir vaka çalışması olarak ele alınmıştır. Modelleme çalışması, Gazimağusa bölgesinin iklimsel verileri kullanılarak MATLAB ortamında gerçekleştirilmiştir. PV sistemi ile üretilen elektrik enerjisi, hem RO ünitesinin tatlı su üretiminde hem de SWHP sisteminin ısıtma ve soğutma yüklerinde kullanılmıştır. Sonuçlar, entegre sistemin yıl boyunca pozitif enerji dengesi ile çalışabildiğini ve özellikle yaz aylarında PV üretim fazlası sayesinde RO su üretiminin maksimum seviyelere ulaştığını göstermiştir. SWHP modülünün COP değerleri 3–5 aralığında gerçekleşmiş, deniz suyu sıcaklığının yüksek olduğu dönemlerde sistem verimliliği artmıştır. Bu entegre modelin, KKTC gibi küçük ada devletlerinin sürdürülebilir kalkınma hedeflerine ulaşmasında kritik bir rol oynayabileceği; enerji verimliliği, karbon emisyonlarının azaltılması ve su kaynaklarının yönetimi açısından önemli katkılar sunabileceği öngörülmektedir. Çalışma, ada ölçeğinde yenilenebilir enerji tabanlı su ve ısı sistemlerinin bütüncül olarak değerlendirilmesi için bir temel oluşturmakta ve benzer coğrafyalarda uygulanabilecek sürdürülebilir bir çözüm önermektedir.

Anahtar Kelimeler: Fotovoltaik (FV), Ters ozmos (TO), Deniz suyu kaynaklı ısı pompası (DSIP), Kuzey Kıbrıs Türk Cumhuriyeti (KKTC)

INTEGRATED ASSESSMENT OF PHOTOVOLTAIC, REVERSE OSMOSIS, AND SEAWATER HEAT PUMP SYSTEMS IN THE CONTEXT OF ENERGY AND WATER SUSTAINABILITY: A CASE STUDY FOR THE TURKISH REPUBLIC OF NORTHERN CYPRUS

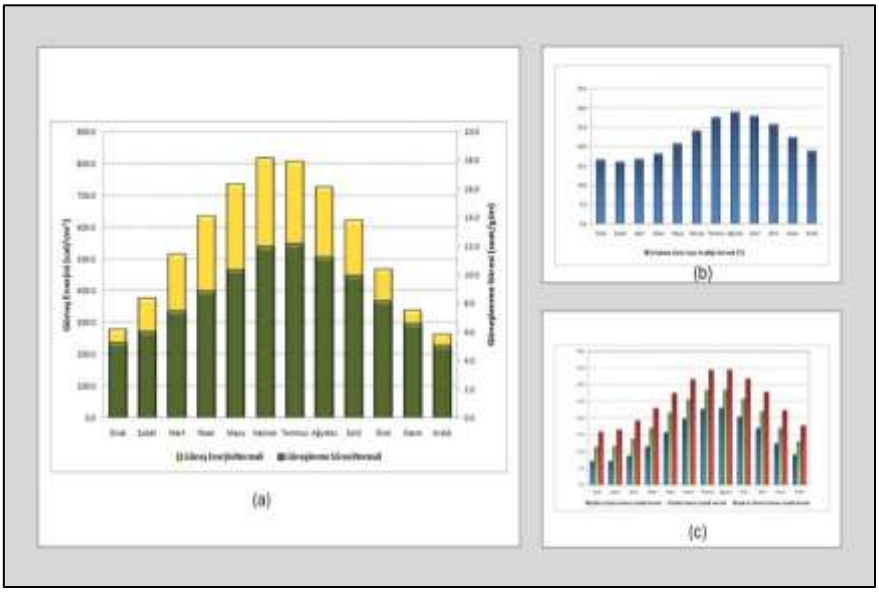
ABSTRACT

Small island states face persistent challenges in energy and water supply due to high dependence on imports, elevated fossil fuel costs, and increasing climate change pressures. These challenges necessitate the development of innovative, sustainable systems capable of ensuring long-term resource security. This study investigates the integration of photovoltaic (PV) panels, reverse osmosis (RO) desalination, and seawater heat pump (SWHP) technologies as a holistic solution to improve energy and water security, using the Turkish Republic of Northern Cyprus (TRNC) as a case study. The modeling process was conducted in MATLAB using the climatic data of the Famagusta region. Electricity generated by PV panels was utilized simultaneously to power the RO desalination unit and the SWHP system for heating and cooling loads. The results indicated that the integrated configuration operated with a positive net energy balance throughout the year. During summer months, the high solar irradiance levels led to maximum RO water production, while the SWHP exhibited coefficients of performance (COP) ranging between 3 and 5, achieving higher efficiency when seawater temperatures increased. The findings suggest that this integrated model can play a critical role in advancing the sustainable development goals of small island regions such as the TRNC. It offers significant potential for improving energy efficiency, reducing carbon emissions, and enhancing water resource management. Overall, the study provides a framework for the combined use of renewable energy, desalination, and thermal systems, proposing a scalable and sustainable solution applicable to similar coastal and island environments.

Keywords: Photovoltaic (PV), Reverse Osmosis (RO), Seawater Heat Pump (SWHP), Turkish Republic of Northern Cyprus (TRNC)

GİRİŞ

Kuzey Kıbrıs Türk Cumhuriyeti gibi küçük ada ekonomileri, izole ve sınırlı kaynaklara sahip olmaları nedeniyle enerji ve su temininde önemli zorluklarla yüzleşmektedir [1]. KKTC'nin elektrik enerjisi üretiminin büyük ölçüde ithal fosil yakıtlara dayanması, enerji maliyetlerini ve karbon ayak izini artırmaktadır. Benzer şekilde, artan nüfus ve kuraklık riski, kısıtlı yeraltı su kaynakları üzerinde ciddi bir baskı oluşturmakta ve su güvenliğini tehdit etmektedir. Adanın yıllık ortalama güneşlenme süresi oldukça yüksek olup, fotovoltaik enerji üretimi için büyük bir potansiyel barındırmaktadır (Şekil 1) [2]. Su kaynakları açısından ise, yeraltı sularının aşırı çekimi ve tuzlanma riski önemli bir sorundur. Türkiye'den deniz altı boru hattı ile su temini projesi su arzına önemli bir katkı sağlasa da, yerel ve sürdürülebilir su kaynaklarının geliştirilmesi stratejik önemini korumaktadır [3]. Özellikle turizm bölgeleri (Gazimağusa) ve kıyı yerleşimlerinde su ve enerji talebi yoğundur. Bu bağlamda, adanın bol güneş enerjisi potansiyelinden ve çevresindeki denizden faydalanarak yenilikçi ve sürdürülebilir çözümler geliştirmesi stratejik bir önem taşımaktadır.



Şekil 1. KKTC meteorolojik verileri, (a) Güneş ışınımı, (b) Deniz suyu sıcaklığı, (c) Hava sıcaklığı [2]

Fotovoltaik sistemlerle entegre ters ozmos (PV-RO) tuzdan arındırma ve ısıtma-soğutma ihtiyaçları için deniz suyu kaynaklı ısı pompaları (SWHP), bu zorluklara yanıt verebilecek iki öncü teknoloji olarak öne çıkmaktadır. Bu iki sistemin entegrasyonu, enerji ve su döngüleri arasında bir sinerji yaratarak kaynak verimliliğini maksimize etme potansiyeli taşımaktadır. Bu çalışma, böyle bir entegre sistemin teknik ve ekonomik fizibilitesini KKTC bağlamında değerlendirmeyi amaçlamaktadır.

Ters ozmos, deniz suyundan tatlı su elde etmek için en yaygın kullanılan teknolojilerden biridir, ancak yüksek enerji tüketimi en büyük dezavantajıdır [4]. PV panellerin RO sistemlerine entegrasyonu, özellikle şebekeden uzak veya elektrik maliyetlerinin yüksek olduğu bölgeler için cazip bir çözüm sunmaktadır. Literatürdeki çalışmalar, PV-RO sistemlerinin küçük ölçekli uygulamalardan büyük tesislere kadar geniş bir yelpazede teknik olarak uygulanabilir olduğunu göstermektedir [5-7]. Bu sistemlerin tasarımı, güneş ışınımının değişkenliğine bağlı olarak kesintisiz su üretimi sağlamak amacıyla genellikle enerji depolama (batarya) birimlerini de içermektedir [5]. Yapılan tekno-ekonomik analizler, PV panellerin maliyetindeki düşüşle

birlikte, PV-RO sistemlerinin geleneksel yöntemlere kıyasla rekabet gücünün arttığını ortaya koymaktadır [5, 6].

Deniz suyu kaynaklı ısı pompaları (SWHP), kışın ısıtma için deniz suyunu ısı kaynağı, yazın ise soğutma için bir ısı çukuru olarak kullanan yüksek verimli sistemlerdir [8]. Deniz suyunun sıcaklığının yıl boyunca havaya göre daha kararlı olması, SWHP hava kaynaklı ısı pompalarına göre daha yüksek ve stabil bir performans katsayısına (COP) sahip olmasını sağlar [9]. Özellikle Akdeniz iklim kuşağında, kıyı şeridindeki oteller, konutlar ve ticari binalar için ısıtma, soğutma ve sıcak su temininde önemli enerji tasarrufu potansiyeli sunmaktadır. SWHP sistemleri, titanyum eşanjörler gibi korozyona dayanıklı malzemeler gerektirse de, uzun vadede işletme maliyetlerini önemli ölçüde düşürebilir.

PV-RO ve SWHP sistemlerinin entegrasyonu üzerine yapılan çalışmalar henüz sınırlı olmakla birlikte, bu iki teknolojinin bir arada kullanılmasının önemli avantajlar sağlayacağı açıktır. PV sistemi, hem RO tesisinin hem de SWHP elektrik ihtiyacını karşılayarak fosil yakıt tüketimini ve işletme maliyetlerini azaltabilir. Ayrıca, RO tesisinden çıkan ve sıcaklığı bir miktar düşmüş olan deniz suyu, SWHP soğutma çevriminde kullanılarak sistemin verimliliğini artırabilir. Bu tür entegre yaklaşımlar, kaynakların daha verimli kullanılmasını sağlayarak döngüsel ekonomi prensiplerine de katkıda bulunur.

Çalışma, KKTC iklim koşulları temelinde geliştirilen bir enerji-su dengesi yaklaşımını ele alır. Sistem, MATLAB [10] tabanlı bir modelleme ortamında, PV üretimi ile RO ve SWHP talepleri arasındaki zaman bazlı enerji akışını inceler. Böylece, ada ölçeğinde yenilenebilir enerji kaynaklarının su üretimi ve termal sistemlerle bütünleşik kullanımının teknik uygulanabilirliği değerlendirilmektedir.

MATERYAL & METOT

Modelleme, üç temel alt modül üzerine kuruludur: PV enerji üretimi, ters ozmos su üretimi, ve deniz suyu ısı pompası performansı. Her bir modül, saatlik veya günlük zaman adımlarında çalıştırılarak, enerji ve su akışlarının dinamik dengesi elde edilir.

Bir PV sisteminin üreteceği enerji (E_{PV}), anlık güneş radyasyonu (G_t) ve panel sıcaklığına bağlı olarak hesaplanır (Eş.1) [11]:

$$E_{PV} = A_{PV} \times G_t \times \eta_{PV(T)} \times PR \quad (1)$$

Burada; A_{PV} toplam PV panel alanını (m^2), G_t ortalama global güneş ışınımını (kWh/m^2), $\eta_{PV(T)}$ sıcaklığa göre değişen PV panel verimliliğini (%)(Eş. 2) ve PR performans oranını (sistem kayıpları 0.75-0.85) ifade etmektedir.

$$\eta_{PV(T)} = \eta_{ref}[1 - \beta[T_{hücre} - 25)] \quad (2)$$

β sıcaklık katsayısını göstermektedir ve yaklaşık olarak 0.004-0.005 1/ºC değerindedir.

RO sisteminin spesifik enerji tüketimi (SEC_{RO}), üretilen her bir metreküp su için harcanan enerjiyi ifade eder (kWh/m^3). Toplam enerji ihtiyacı (E_{RO}) Eşitlik 3 ile bulunur [4]:

$$E_{RO} = V_{su} \times SEC_{RO} \quad (3)$$

SEC_{RO} deniz suyu için tipik olarak 3-5 kWh/m^3 arasındadır.

SWHP performansı, deniz suyu sıcaklığı (T_{sea}) ve ortam sıcaklığı (T_{air}) farkına bağlıdır. Performans katsayısı (COP) Eşitlik 4 ile bulunur [9]. Deniz suyunun kararlı sıcaklığı sayesinde $SWHP_{COP}$ değerleri genellikle 4 ila 6 arasında değişir, bu da onları oldukça verimli

kılar. Buna bağlı olarak ısıtma/soğutma için gerekli enerji ihtiyacı (E_{SWHP}) Eşitlik 5 ile hesaplanmaktadır.

$$SWHP_{COP} = \frac{T_{evap}+273}{T_{cond}-T_{evap}} \quad (4)$$

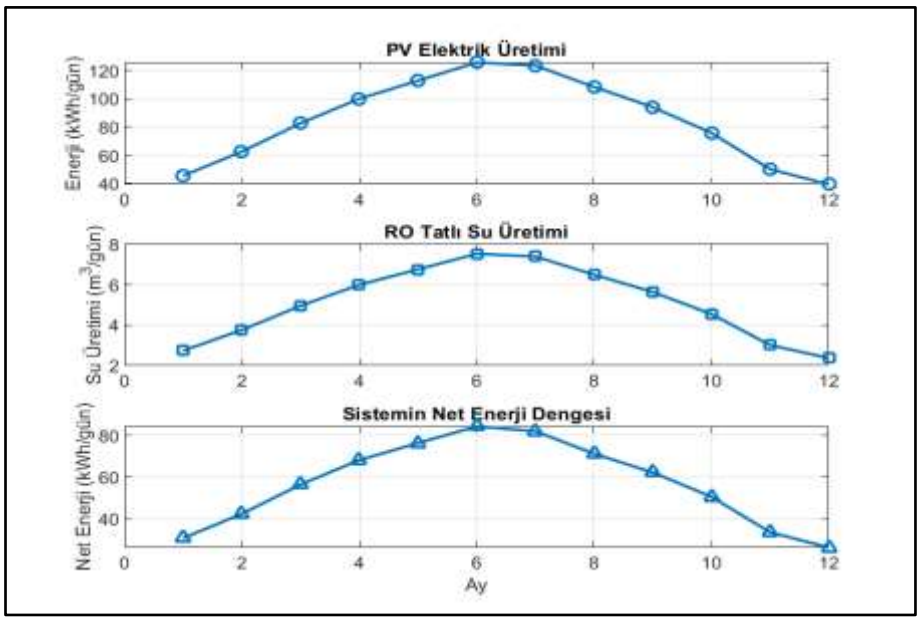
$$E_{SWHP} = \frac{\dot{Q}_{yük}}{SWHP_{COP}} \quad (5)$$

Toplam sistem dengesi Eşitlik 6 ile bulunur. Pozitif değer enerji fazlasını, negatif değer ise sistemin dış kaynak ihtiyacını gösterir.

$$E_{net} = E_{PV} - (E_{RO} + E_{SWHP}) \quad (6)$$

BULGULAR

Gazimağusa koşullarına göre oluşturulan PV–RO–SWHP entegre modelinin sonuçları Şekil 2'de verilmiştir. Güneşlenme değerlerinin mevsimsel değişimi, sistemin enerji üretimi ve su çıktıları üzerinde doğrudan etkili olmuştur.



Şekil 2. Çalışma özeti.

PV elektrik üretimi, yıl boyunca 40–130 kWh/gün aralığında değişmiştir. En yüksek üretim haziran–temmuz döneminde gözlenmiş, bu dönemde ortalama güneşlenme 340–360 W/m^2 civarına ulaşmıştır. Kış aylarında üretim 40–60 kWh/gün düzeyine düşmüştür. Bu sonuç, ada ölçeğinde PV tabanlı enerji sistemlerinin mevsimsel dalgalanmaya duyarlı olduğunu göstermektedir.

RO tatlı su üretimi, PV üretimiyle orantılı olarak artış göstermiştir. Haziran ve temmuz aylarında günlük ortalama 7–8 m^3 su üretimi sağlanmıştır. Kış aylarında bu miktar 2–3 m^3/gün seviyelerine kadar gerilemiştir. Bu durum, PV üretim fazlasının doğrudan RO ünitesine yönlendirilmesinin ada su arzında etkin bir strateji olduğunu ortaya koymaktadır.

Sistemin net enerji dengesi, yıl boyunca pozitif değerler göstermiştir; yani PV üretimi, RO ve SWHP tüketimlerinin toplamını karşılayabilmiştir. En yüksek net enerji değeri yaklaşık 85 kWh/gün ile yaz ortasında elde edilmiştir. Bu değer, sistemin dış enerjiye bağımlı olmadan

çalışabildiği dönemi temsil etmektedir. Kış aylarında ise net enerji 30–40 kWh/gün düzeyine inmiş, bu da düşük ışınım koşullarında sistemin sınırlı performansını göstermektedir.

Genel olarak model, PV kaynaklı elektrik üretiminin ada ölçeğinde hem tatlı su üretimi hem de ısıtma/soğutma yüklerini aynı anda karşılayabilecek düzeyde olduğunu ortaya koymaktadır. SWHP modülünün COP değerleri 3–5 aralığında gerçekleşmiş, özellikle deniz suyu sıcaklığının 24–27 °C'ye ulaştığı yaz aylarında sistemin toplam verimi artmıştır.

Sonuçlar, entegre PV–RO–SWHP sisteminin Gazimağusa gibi küçük ada yerleşimlerinde enerji-su-ısı yönetimi açısından sürdürülebilir ve uygulanabilir bir çözüm sunduğunu göstermektedir. Model, ada ölçeğinde mevsimsel planlama yapılmasına olanak tanıyan bir araç niteliği taşımaktadır.

SONUÇLAR & ÖNERİLER

Fotovoltaik paneller, ters ozmos ve deniz suyu kaynaklı ısı pompası teknolojilerinin entegrasyonu, KKTC gibi küçük ada devletlerinin karşılaştığı enerji ve su sorunlarına sürdürülebilir ve yenilikçi bir çözüm sunma potansiyeline sahiptir. Bu entegre yaklaşım, fosil yakıtlara olan bağımlılığı azaltarak enerji güvenliğini artırmakta, su kıtlığına karşı yerel ve güvenilir bir kaynak yaratmakta ve ısıtma-soğutma süreçlerinde enerji verimliliği sağlayarak ekonomik fayda üretmektedir.

Model sonuçları, PV-RO-SWHP sisteminin Gazimağusa iklim koşullarında yıl boyunca pozitif enerji dengesi ile çalışabildiğini ve su üretimini istikrarlı şekilde sürdürebildiğini göstermiştir. Özellikle yaz aylarında güneşlenmenin artmasıyla birlikte, sistemin hem enerji fazlası oluşturduğu hem de su üretimini maksimum seviyeye ulaştırdığı gözlemlenmiştir. Bu durum, adalar için yenilenebilir tabanlı trijenerasyon yaklaşımının teknik olarak uygulanabilir olduğunu doğrulamaktadır.

KKTC'nin coğrafi ve iklimsel özellikleri, bu tür sistemlerin uygulanması için oldukça elverişlidir. Uzun kıyı şeridi ve yüksek güneşlenme süresi, PV tabanlı elektrik üretimi ile deniz suyu kaynaklı ısı pompası teknolojisinin birlikte değerlendirilmesini kolaylaştırmaktadır. Özellikle kıyı bölgelerinde yer alan oteller ve turistik tesisler, hem yüksek su tüketimi hem de yoğun iklimlendirme gereksinimleri nedeniyle bu entegre modelin en uygun uygulama alanlarını oluşturmaktadır.

Bu tesislerin çatılarına veya yakın arazilerine kurulacak PV sistemleri, hem içme ve kullanma suyu üretecek RO tesislerini hem de ısıtma-soğutma hizmeti sağlayacak SWHP sistemlerini besleyebilir. Böyle bir uygulama, işletme maliyetlerini düşürürken aynı zamanda çevre dostu "yeşil otel" konseptini destekler ve pazarlama açısından da avantaj sağlar. Yeni gelişen kıyı yerleşimlerinde merkezi veya dağıtık ölçekli entegre sistemlerin kurulması, şebeke üzerindeki yükü azaltarak bölge halkına daha düşük maliyetli ve güvenilir su ve iklimlendirme hizmetleri sunulmasına olanak verebilir.

Ayrıca, PV-RO sistemleri tarımsal sulama için gerekli tatlı suyun üretiminde de değerlendirilebilir. Bu sayede yeraltı su kaynakları üzerindeki baskı azalacak, tarımsal üretimin sürdürülebilirliği desteklenecektir. Sistem, uzun vadede işletme maliyetlerinin düşürülmesi, karbon emisyonlarının azaltılması ve su kaynaklarının korunması açısından da önemli faydalar sunmaktadır.

Sonuç olarak, PV–RO–SWHP entegre modelinin, KKTC'nin sürdürülebilir kalkınma hedeflerine ulaşmasında, özellikle turizm ve yerleşim bölgelerinde yaşam kalitesini artırma yönünde stratejik bir araç olabileceği değerlendirilmektedir.

Gelecek çalışmalarda KKTC'de seçilecek pilot bir bölgede detaylı fizibilite çalışması, dinamik simülasyonlar ve yaşam döngüsü maliyet analizleri yapılarak yatırımın geri dönüş sürelerinin belirlenmesi önerilmektedir. Ayrıca, bu teknolojilerin yaygınlaşmasını destekleyecek yasal düzenlemelerin ve teşvik mekanizmalarının geliştirilmesi, sistemin ada genelinde benimsenmesini hızlandıracaktır.

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AĞIRLIKLI AKSİYOMATİK TASARIM KULLANARAK BELİRSİZLİKLERE DAYANIKLI ELEKTRİKLİ ARAÇ ÖNERİ SİSTEMİ GELİŞTİRİLMESİ

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ÖZET

Elektrikli araçların (EA) giderek yaygınlaşması, tüketicilerin karmaşık ve dinamik piyasalarda ürün alternatiflerini değerlendirmelerine yardımcı olabilecek sistematik ve belirsizliğe odaklı karar destek çerçevelerine olan ihtiyacı ortaya koymaktadır. Bu çalışma, EA değerlendirmelerinde öznel algıları ve belirsiz değerlendirmeleri etkin bir şekilde yakalamak için bulanık–bulanık sistem–tasarım eşleştirmeleri kullanan Aksiyomatik Tasarım (AT) tabanlı bir öneri modelini tanıtmaktadır. Bu çerçevede, konfor, uygun fiyat ve menzil gibi elektrikli araç seçiminde etkili faktörler bulanık sayılarla temsil edilmekte, böylece model, kullanıcı değerlendirmeleri ve ürün özelliklerinde yer alan algısal belirsizlik ve muğlaklığı ifade edebilmektedir. Modelin gerçekçiliğini ve karar duyarlılığını artırmak için, bireysel kriterlerin göreli önemini içerecek şekilde ağırlıklı bir AT formülasyonu önerilmiş, bilgi içeriğinin hesaplanması iyileştirilmiş ve karar ayrımı güçlendirilmiştir. Önerilen model, çeşitli özelliklerin bulanık değerlendirmeleri içeren bir EA veri seti üzerinde gösterilmiştir. Bulgular, bulanık modelleme ve kriter ağırlıklandırmasının entegrasyonunun çerçevenin yorumlanabilirliğini, duyarlılığını ve gerçek dünya karar davranışlarıyla uyumunu önemli ölçüde artırdığını göstermektedir. Bu çalışma, Aksiyomatik Tasarımın teorik ve pratik uygulanabilirliğini bulanık karar ortamlarına genişleterek literatüre katkıda bulunmakta ve EA alanında zeki, belirsizliğe dayanıklı öneri sistemlerinin geliştirilmesi için sağlam bir metodolojik temel sunmaktadır.

Anahtar Kelimeler: Aksiyomatik tasarım; Öneri sistemleri; Elektrikli araç seçimi; Karar destek; Bulanık mantık

TOWARD AN UNCERTAINTY-TOLERANT ELECTRIC VEHICLE RECOMMENDATION SYSTEM VIA WEIGHTED AXIOMATIC DESIGN

ABSTRACT

The increasing adoption of electric vehicles (EVs) highlights the need for systematic and uncertainty-oriented decision-support frameworks that can assist consumers in evaluating product alternatives in complex and dynamic markets. This study introduces an Axiomatic Design (AD)–based recommendation model that employs fuzzy–fuzzy system–design pairings to effectively capture subjective perceptions and imprecise evaluations in EV assessments. Within this framework, factors influencing electric vehicle selection—such as comfort, affordability, and driving range—are represented using fuzzy numbers, allowing the model to express perceptual vagueness and uncertainty inherent in user evaluations and product characteristics. To improve the model's realism and decision sensitivity, a weighted AD formulation is proposed to incorporate the relative importance of individual criteria, refining the computation of information content and enhancing decision discrimination. The proposed model is demonstrated through a dataset of EVs featuring fuzzy evaluations of diverse attributes. The findings indicate that the integration of fuzzy modeling and criterion weighting significantly enhances the framework's interpretability, responsiveness, and alignment with real-world decision behavior. This study contributes to the literature by extending the theoretical and practical applicability of Axiomatic Design to fuzzy decision environments, while providing a rigorous methodological foundation for developing intelligent, uncertainty-tolerant recommendation systems in the EV domain.

Keywords: Axiomatic design; Recommendation systems; Electric vehicle selection; Decision support; Fuzzy logic

1. INTRODUCTION

The widespread adoption of electric vehicles (EVs) continues to accelerate due to growing environmental pressures, government incentives, and significant improvements in charging infrastructure and battery technologies. Global commitments to phase out high–fossil-fuel–consuming vehicles by 2030, supported by new legislative measures and national transition plans, further reinforce this shift (Ibrahim et al., 2023). However, EV selection remains a complex multi-criteria decision-making (MCDM) problem, as consumers and policymakers must simultaneously evaluate cost, driving range, battery performance, charging accessibility, safety, environmental impact, and brand reliability. This complexity is intensified by uncertainties in key performance parameters, often caused by incomplete data or inconsistencies in manufacturer-reported specifications. Therefore, transparent and uncertainty-sensitive decision-support methods are essential for guiding stakeholders toward the most appropriate EV choice.

Axiomatic Design (AD) offers a structured theoretical framework for organizing and evaluating decision problems under uncertain conditions. Its core principles—the independence and information axioms—enable a formal assessment of how effectively design parameters meet functional requirements. Incorporating fuzzy representations into AD enhances its capacity to address real-world decision-making scenarios, where uncertainty may result from subjective evaluations, imprecise data, or variable system conditions. In this research, we introduce a fuzzy-based AD approach to facilitate EV evaluation and recommendation under uncertain circumstances. Relevant vehicle characteristics—such as driving range, charging time, battery capacity, and performance measures—are expressed as fuzzy variables, reflecting both intrinsic imprecision and ambiguity in user judgments. The information axiom is applied to assess the degree of correspondence between user preferences and fuzzy design parameters, enabling a systematic, uncertainty-sensitive ranking of EV alternatives. By combining fuzzy modeling with AD methodology, the proposed framework improves the realism, robustness, and clarity of decision-making, offering a strong foundation for developing intelligent and uncertainty-tolerant recommendation systems in the electric mobility domain.

2. METHODOLOGY

2.1 Axiomatic Design Methodology

The Axiomatic Design (AD) approach offers a systematic framework for translating complex customer requirements into corresponding functional requirements (FRs) and design parameters (DPs). Its main purpose is to improve the rationality and quality of design and decision-making by incorporating fundamental design principles, known as axioms, into the analytical process. First proposed by Suh (1990), AD provides a general methodology to ensure that system designs are logically coherent and information-efficient. The methodology rests on two core axioms: the Independence Axiom, which requires that each functional requirement is fulfilled independently, and the Information Axiom, which aims to minimize the system's information content to produce more reliable and effective designs. Together, these axioms allow a structured evaluation of how well a system's parameters satisfy functional requirements under diverse conditions. When applied to decision environments involving uncertainty, AD demonstrates significant advantages in handling imprecise and variable data. Instead of relying on deterministic assumptions, AD can represent each design parameter or criterion as a fuzzy variable, capturing the inherent uncertainty due to incomplete information, measurement variability, or environmental fluctuations. As noted by Kulak et al. (2010) and Baykasoglu et al. (2024), AD is particularly suitable for multi-criteria decision-making (MCDM) contexts

because it supports hierarchical problem decomposition, facilitates the assessment of fuzzy-defined criteria, and maintains analytical rigor despite uncertainty or incomplete data. Its capability to manage heterogeneous data and systematically quantify uncertainty makes AD a robust foundation for developing interpretable, reliable decision-support systems, especially in complex domains such as electric vehicle evaluation.

2.1.1 Fuzzy Axiomatic Design

In applied decision-making contexts, the specifications of functional requirements (FRs) for both system and design are typically characterized by uncertainty and vagueness. To capture such uncertainty, the Axiomatic Design (AD) framework can be adapted to a fuzzy environment, representing both design and system variables as fuzzy numbers (d and s). These fuzzy representations capture parameter variability more realistically than deterministic values. As shown in Figure 1, a design is considered acceptable when the fuzzy variables exhibit sufficient overlap, delineating a feasible region in which the functional requirement is partially or fully met. The extent of this overlap indicates how effectively the design fulfills its intended performance under uncertainty, supporting a more robust and interpretable decision-making process.

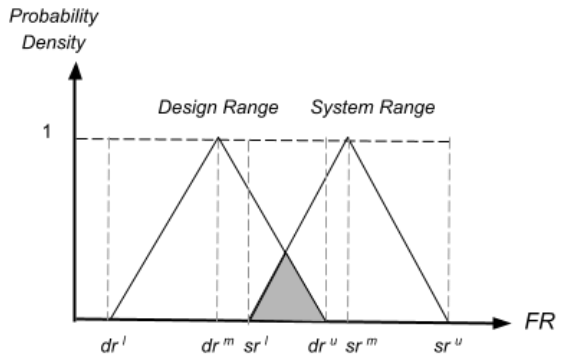

Figure 1. Diagram of design and system ranges in fuzzy decision-making environments.
Source(s): Subulan and Baykasoglu (2021)

Assuming a uniform probability distribution for the functional requirement, the probability of its satisfaction can be determined according to Equation 1.

$$p_j = Common\ Range\ /\ System\ Range \tag{1}$$

Equation (2) presents the expression for the information content (I_j) of any FR_jwithin fuzzy environments.

$$I_j = \log_2\left(\frac{1}{p_j}\right) \quad or \quad \log_2\left(System\ Range\ /\ Common\ Range\right) \tag{2}$$

To demonstrate the evaluation of partial satisfaction for a user requirement, an example scenario is provided in which the information content of the price criterion is calculated for a candidate alternative. This calculation is based on the intersection area between the fuzzy representation of the user-defined requirement and the system-provided value, reflecting the degree to which the alternative aligns with user expectations. Let the vehicle's price be represented as the triangular fuzzy number (110, 160, 210), where 110, 160, and 210 denote the minimum, most likely, and maximum prices, respectively. The design requirement for price is defined as the triangular fuzzy number (50, 100, 150), representing the minimum desired price, the target price, and the maximum tolerable price. The corresponding graphical representation is shown in Figure 2.

Information content is first calculated for each criterion and then weighted using normalized criterion weights. A cumulative I value for each alternative is obtained by aggregating these weighted values, and alternatives are ranked in ascending order, with the most preferred option having the lowest I value. This methodology enables the framework to systematically quantify both full and partial satisfaction of requirements, providing a transparent and structured foundation for evaluating and comparing electric vehicle alternatives.

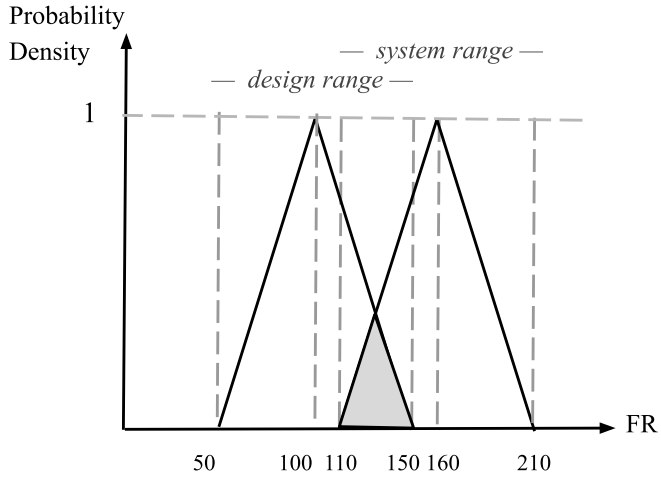

Figure 2. Fuzzy-Based System and Design Range for Alternative 4: Price Criterion

Based on the overlapping region, the I value is determined to be 2.644 using the formula provided below (3):

$$I = log_2\left(\frac{(sU-sL).(dU-dM)+(sU-sL).(sM-sL)}{(\mathrm{dU}-\mathrm{sL})^2}\right) \qquad if\ \ dL < sL < dU < sU \tag{3}$$

2.1.2 Weighted Axiomatic Design

From the decision maker's viewpoint, functional requirements (FRs) frequently vary in their relative importance. Each criterion may be allocated a weight w to more accurately capture its significance in realistic decision-making scenarios. For hierarchical decision-making, the cumulative weight of a functional requirement FR_i is computed as the product of the weights at all levels of the hierarchy relevant to that requirement, with k representing the number of levels.

Weighted information content is computed following the methodology initially introduced by Kulak and Kahraman (2005), refined by Shahbandarzadeh et al. (2011), and further extended by Subulan and Baykasoglu (2021). The weighted information content WI_{ij} is defined as follows (4):

$$WI_{ij} = \begin{cases} \left[\left|\log_2\left(\frac{1}{p_{ij}}\right)\right|^{\frac{1}{\prod_{k\epsilon K} W_{kj}}}\right] & 0 \le I_{ij} \le 1 \\ \left[\left|\log_2\left(\frac{1}{p_{ij}}\right)\right|^{\left(\prod_{k\epsilon K} W_{kj}\right)}\right] & I_{ij} > 1 \\ \prod_{k\epsilon K} W_{kj} & I_{ij} = 1 \\ -\left[\left|\log_2\left(\frac{1}{p_{ij}}\right)\right|^{1-\left(\prod_{k\epsilon K} W_{kj}\right)}\right] & -1 < I_{ij} \le 0 \\ -\left[\left|\log_2\left(\frac{1}{p_{ij}}\right)\right|^{1+\left(\prod_{k\epsilon K} W_{kj}\right)}\right] & I_{ij} \le -1 \\ -\left(1+\left(\prod_{k\epsilon K} W_{kj}\right)\right) & I_{ij} = -1 \end{cases} \quad (4)$$

This weighted formulation allows the Axiomatic Design framework to reflect the relative importance of individual criteria, enhancing the accuracy of information content calculations and improving decision discrimination in hierarchical and multi-criteria contexts.

3. DATA COLLECTION

To demonstrate the applicability of the proposed fuzzy-based Axiomatic Design (AD) framework, a dataset of nine electric vehicle (EV) models was constructed using information adapted from Ziemba's (2021) study. From the available attributes, five criteria—price, driving range, charging time, energy consumption, and vehicle appearance—were selected for analysis, as these parameters inherently involve subjective judgments, measurement variability, or context-dependent performance. Among these, price may fluctuate due to minimum–maximum equipment configurations, optional features, and market-related adjustments, while driving range and energy consumption are influenced by driving habits, temperature, and battery aging; charging time varies across charging infrastructure and operational conditions; and vehicle appearance reflects user perceptions that are intrinsically imprecise. Owing to these sources of uncertainty and subjectivity, each criterion is modeled using fuzzy representations, enabling the framework to more accurately reflect real-world evaluation ambiguity. These selected variables thus provide an appropriate foundation for implementing the fuzzy AD methodology. A concise overview of the dataset is presented in Table 1.

4. CASE STUDY

A case study demonstrating the application of the proposed fuzzy-based Axiomatic Design (AD) framework for electric vehicle (EV) recommendation is presented in this section. In this approach, all relevant decision variables are modeled as fuzzy numbers, enabling a systematic representation of the uncertainty, imprecision, and variability inherent in vehicle specifications and performance metrics. This fuzzy formulation also allows the model to capture real-world variability in EV attributes, such as fluctuations in energy consumption driven by ambient temperature, driving intensity, or battery efficiency. The resulting recommendation system is highly flexible, permitting users to define functional requirements (FRs) and design parameters (DPs) according to their individual evaluation criteria and decision-making priorities.

Table 1. Dataset of EVs with a diverse set of attributes

Alternatives / Criteria	A1 Renault ZOE ZE40 R110	A2 Renault ZOE ZE40 R90	A3 Smart EQ forfour	A4 BMW i3	A5 BMW i3s	A6 Hyundai IONIQ Electric	A7 Volkswagen e-Golf	A8 Nissan LEAF	A9 Nissan LEAF e+
C1 Price (PLN thousand)	(144.4, 151.0, 157.6)	(133.9, 140.1, 146.3)	(96, 108, 120)	(169, 199, 229)	(183.4, 210.3, 237.2)	(164.5, 179.5, 194.6)	(141.9, 168., 194.2)	(157.7, 173.6, 189.5)	(195.6, 203.3, 211.1)
C2 Range (km)	(180, 290, 400)	(180, 290, 400)	(65, 112.5, 160)	(165, 296.5, 428)	(160, 282.5, 405)	(135, 212.5, 290)	(135, 217.5, 300)	(155, 272, 389)	(230, 379, 528)
C3 Charging Time (min)	(135, 817.5, 1500)	(135, 817.5, 1500)	(55, 290, 525)	(255, 712.5, 1170)	(255, 712.5, 1170)	(270, 570, 870)	(315, 667.5, 1020)	(390, 825, 1260)	(600, 1260, 1920)
C4 Energy Consumption (kWh / 100 km)	(10.5, 16.6, 22.8)	(10.4, 16.6, 22.8)	(10.4, 18.05, 25.7)	(10.4, 17.05, 23.7)	(10.7, 17.2, 23.7)	(9.7, 15.2, 20.7)	(10.7, 17.2, 23.7)	(10.3, 16.75, 23.2)	(11.5, 17.9, 24.3)
C5 Vehicle Appearance	(4.2, 5.6, 7)	(4.2, 5.6, 7)	(2.2, 3.3, 4.4)	(3.2, 4.4, 5.6)	(3.2, 4.4, 5.6)	(6, 7.2, 8.4)	(5, 6.2, 7.4)	(6.4, 7.5, 8.6)	(6.4, 7.5, 8.6)

An illustrative example of user-specified requirements is provided in Table 2. In this case study, the user articulated their requirements using fuzzy variables and assigned weights to each criterion based on its relative importance in their decision process.

Table 2. User-defined requirements

Criteria	User Requirements	User Weight
C1 - Price (PLN thousand)	(100, 175, 250)	1
C2 - Range (km)	(200, 375, 550)	5
C3 - Charging Time (min)	(100, 800, 1500)	5
C4 - Energy Consumption (kWh / 100 km)	(10, 15, 20)	1
C5 - Vehicle Appearance	(4, 7, 10)	1

5. FINDINGS

The application of the proposed methodology to the case study resulted in eight out of nine electric vehicles being recommended, with their rankings determined by ordering the computed I values from lowest to highest. Initially, the methodology was executed with equal weighting

across all criteria, followed by an analysis incorporating user-defined weights to capture personal priorities. The corresponding recommendations are presented in Figures 3 and 4. Alternative A3 is omitted from subsequent analysis due to its inability to meet a key criterion—driving range. Within the proposed framework, failure to meet even a single requirement is sufficient to remove an alternative from consideration. To remain eligible for recommendation, each option must fulfill all specified requirements either fully or to an acceptable degree. A fully satisfied requirement results in an information content value of $I = 0$, while partial satisfaction generates a positive I value, calculated in accordance with the information axiom.

ListingID	Price	Range	ChargingTime	EnergyConsumption	VehicleAppearance	IValue
A1	151+-6.6	290+-110	817.5+-682.5	16.6+-6.2	5.6+-1.4	0.072483
A2	140.1+-6.2	290+-110	817.5+-682.5	16.6+-6.2	5.6+-1.4	0.072483
A6	179.5+-15.1	212.5+-77.5	570+-300	15.2+-5.5	7.2+-1.2	0.084266
A8	173.6+-15.9	272+-117	825+-435	16.75+-6.45	7.5+-1.1	0.116571
A7	168+-26.2	217.5+-82.5	667.5+-352.5	17.2+-6.5	6.2+-1.2	0.332467
A4	198.9+-30.1	296.5+-131.5	712.5+-457.5	17.05+-6.65	4.4+-1.2	1.348139
A5	210.3+-26.9	282.5+-122.5	712.5+-457.5	17.2+-6.5	4.4+-1.2	1.417920
A9	203.3+-7.8	379+-149	1260+-660	17.9+-6.4	7.5+-1.1	2.030822

Figure 3. EV recommendations generated by the system based on user-defined inputs with equal weights

ListingID	Price	Range	ChargingTime	EnergyConsumption	VehicleAppearance	IValue
A1	151+-6.6	290+-110	817.5+-682.5	16.6+-6.2	5.6+-1.4	0.001088
A2	140.1+-6.2	290+-110	817.5+-682.5	16.6+-6.2	5.6+-1.4	0.001088
A8	173.6+-15.9	272+-117	825+-435	16.75+-6.45	7.5+-1.1	0.003742
A7	168+-26.2	217.5+-82.5	667.5+-352.5	17.2+-6.5	6.2+-1.2	0.196111
A6	179.5+-15.1	212.5+-77.5	570+-300	15.2+-5.5	7.2+-1.2	0.289997
A4	198.9+-30.1	296.5+-131.5	712.5+-457.5	17.05+-6.65	4.4+-1.2	1.065155
A5	210.3+-26.9	282.5+-122.5	712.5+-457.5	17.2+-6.5	4.4+-1.2	1.087915
A9	203.3+-7.8	379+-149	1260+-660	17.9+-6.4	7.5+-1.1	2.055651

Figure 4. EV recommendations generated by the system based on user-defined inputs with different weights

6. DISCUSSION AND CONCLUSION

This study extends the classical Axiomatic Design (AD) framework by developing a fuzzy-based approach to manage uncertainty in real-world decision-making, with a focus on electric vehicle (EV) recommendations. By representing all relevant decision variables as fuzzy numbers, the proposed framework systematically captures the imprecision, variability, and uncertainty inherent in vehicle specifications and performance metrics. The case study demonstrates that the methodology can provide flexible, user-tailored recommendations, accommodating individual preferences through weighted criteria while ensuring that all functional requirements are sufficiently satisfied. The results highlight the framework's capability to rank alternatives robustly and transparently, offering a practical tool for supporting complex decision-making in EV selection and potentially other domains where uncertainty is a critical factor.

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İŞ MAKİNELERİ KAYNAKLI BAĞLANTILARINDA OLUŞAN HASARLAR VE ÖNLEME YÖNTEMLERİ

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ÖZET

Bu derleme çalışmasında, literatürde yer alan bilimsel çalışmalardaki veriler ve öneriler çerçevesinde iş makinelerinde işletme şartlarında karşılaşılan başlıca hasar türleri, hasarların oluşum mekanizmaları ve öneriler değerlendirilmiştir. Yapılan araştırmalar, iş makinelerinde meydana gelen arızaların önemli bir kısmının kaynaklı bağlantılardan kaynaklandığını göstermektedir. Özellikle ekskavatör tipi iş makinaları, yoğun dinamik yükler, darbeli zorlanmalar ve zorlu çevresel koşullar altında çalışan kritik yapısal elemanlardır. Bu sistemlerin en kritik elemanlarından biri olan kaynaklı bağlantılar, yük aktarımında ve yapısal bütünlüğün korunmasında belirleyici bir rol oynayan kepçe gövdesini oluşturan çelik saclar arasındaki kaynaklı bağlantılarda yüksek gerilim yığılmalarına yol açmakta ve zamanla servis şartlarındaki yüklemelere rağmen hasar oluşturabilmektedir. Bununla birlikte kaynaklı birleştirmeler için uygun olmayan Kaynak Prosedür Şartnameleri (WPS'ler) veya kaynak prosesleri sürecinde yapılan işlem hataları, Tahribatsız Muayenenin (NDT) tam veya doğru uygulanmaması gibi faktörler hasarların önemli sebepleridir. Ayrıca, ürünün tasarımı sürecinde, yanlış malzeme seçimi veya şekillendirme sürecinde yapılan hatalar da iş makinalarında meydana gelen hasarların nedenlerindendir. Literatür verileri, ekskavatör bomları, bağlantı noktaları ve benzeri konstrüksiyon parçalarında görülen hasarların çoğunlukla kaynak kökenli yorulma çatlakları ile malzeme uyumsuzluklarından kaynaklandığını ve bu tür hasarların toplam arıza türleri içerisinde önemli bir paya sahip olduğunu ortaya koymaktadır. Bu çalışma ile iş makinelerindeki kaynaklı bağlantı güvenliğini artırmak amacıyla mevcut araştırmaların bütüncül bir bakış açısıyla derlenerek bilimsel bir veri kaynağının oluşturulması hedeflenmiştir.

Anahtar Kelimeler: İş Makineleri, Kaynaklı Bağlantılar, Hasar Analizi, Hasar Mekanizmaları.

FAILURES AND PREVENTION METHODS IN WELDED JOINTS OF CONSTRUCTION MACHINERY

ABSTRACT

In this research study, the main types of failures encountered in construction machinery under operating conditions, the mechanisms of failure formation, and recommendations were evaluated within the framework of scientific studies and data found in the literature. The research conducted shows that a significant percentage of failures occurring in construction machinery are caused by welded joints. Especially excavator-type construction machinery are critical structural elements operating under intense dynamic loads, impact stresses, and harsh environmental conditions. Welded joints, one of the most critical elements of these systems, cause high stress loads in the welded joints between the steel plates that form the bucket body, which plays a decisive role in load transfer and maintaining structural integrity, and can cause damage over time despite the loads under service conditions. However, factors such as Welding Procedure Specifications (WPS) that are not suitable for welded joints or faults in the welding process, such as the incomplete or incorrect application of Non-Destructive Testing (NDT) procedures, are significant causes of failures. Furthermore, wrong material selection during the product design process or faults made during the forming process are also causes of failures in construction machinery. Literature shows that failures in excavator booms, connection parts, and similar construction components are mostly caused by fatigue cracks originating from welding and material incompatibilities, and that such failures account for a significant percentage of total failure types. This study aims to create a scientific knowledge base by reviewing existing research from a comprehensive perspective in order to improve the safety of welded connections in construction machinery.

Keywords: Construction Machinery, Welded Joints, Failure Analysis, Failure Mechanisms.

1. GİRİŞ

Bilim ve teknolojinin gelişimi, insanoğlunun hem ihtiyaçlarını karşılamak hem de daha iyi yaşam koşulları oluşturmak için sürdürdüğü çabaların doğal bir sonucudur. Bu çabanın önemli bir parçası da, işlerin tehlikeli olduğu veya insan yeteneğinin gerekliliğinin azaldığı durumlarda üretim süreçlerini otomatikleştirme isteğidir. Geçmişten bu yana makinelerin ve tezgâhların insan müdahalesi olmadan çalışabilmesi hedeflenmiş olsa da, bu hedefi gerçekleştirmek uzun süre mümkün olmamıştır. Çünkü insanın yeni durumlara uyum sağlama, beklenmeyen koşulları algılama, analiz etme ve makul sonuçlara ulaşma konusundaki üstün yetenekleri, günümüz teknolojisinin dahi tam anlamıyla taklit edemediği özelliklerdir. Bununla birlikte, günümüzde insan tarafından yapılabilen birçok görev, artık elektromekanik ve hidromekanik sistemler tarafından başarıyla yerine getirilebilmektedir. Robotlar ve iş makineleri pek çok imalat faaliyetinin ayrılmaz bir parçası hâline gelmiş, üretim süreçlerinde yaygın olarak kullanılmaya başlanmıştır [1].

Ancak piyasa koşullarındaki dışa bağımlılık ve özellikle döviz kurlarındaki dalgalanmaların artması, iş makineleri kullanıcılarını ve yedek parça tedarikçilerini olumsuz etkilemektedir. Bu ekonomik koşullar altında en rasyonel yaklaşım, mevcut iş makinelerinin ve parçalarının kullanım ömrünü uzatmak, oluşabilecek hasarları erken aşamada tespit ederek büyümeden önlem almaktır [2]. Çünkü hasar, bir yapı ya da elemanın kendisinden beklenen işlevi yerine getiremeyecek hâle gelmesi olarak tanımlanır ve temelde elemanın aşırı zorlanması sonucunda ortaya çıkar. Bu zorlanma iki temel nedenden kaynaklanır: Elemanın dayanımının gerekli düzeyin altında olması veya elemana etki eden yüklerin, elemanın taşıyabileceği sınırları aşması. Dolayısıyla, hasarın doğru analiz edilmesi ve önleyici yaklaşımların benimsenmesi, hem makine verimliliğinin korunması hem de ekonomik kayıpların en aza indirilmesi açısından kritik öneme sahiptir [2,3].

1.1. Hasar ve Hasar Analizi

Hasar, bir yapının veya yapı elemanının kendisinden beklenen performans kriterlerini karşılayamaz hâle gelmesi olarak tanımlanır ve genellikle yapının tasarım, imalat, montaj ya da işletme aşamalarından herhangi birinde ortaya çıkan teknolojik hataların bir sonucudur. Tasarım aşamasında hatalar; hesaplama yetersizlikleri, yanlış mühendislik varsayımları ve uygun olmayan malzeme seçimi gibi unsurları içerir ve bu aşamadaki sorumluluk tasarımcıya aittir. İmalat sürecinde görülen teknolojik kusurlar ise üretim parametrelerindeki uygunsuzluklar ile malzemenin içsel yapısında bulunan hataları kapsar; bu kapsamda sorumluluk üreticiye aittir. Yapının veya sistemin birleştirilmesi sırasında meydana gelen yanlış uygulamalar montaj hatası olarak adlandırılır ve bundan montajı yapanlar sorumludur. İşletme safhasında karşılaşılan hatalar ise çoğunlukla aşırı zorlanma, yanlış kullanım veya yetersiz bakım faaliyetlerinden kaynaklanır ve bu durumun sorumluluğu işletmeciye aittir. Bu aşamaların herhangi birinde yapılan hatalar, zamanla ilerleyerek yapısal bütünlüğün bozulmasına ve nihai olarak elemanın işlev kaybına neden olabilmektedir [5].

Parçalarda oluşan hasarların tamamen önlenmesi ise mümkün değildir [5].

- Hasar Türleri

Hasarın sınıflandırılması farklı yaklaşımlara göre değişiklik gösterebilmekte olup, kullanılan sınıflandırma sistemine bağlı olarak malzemelerde ortaya çıkan fiziksel hasarlar çeşitli kategoriler altında incelenmektedir. Hasarın tanımlanması, nedenlerinin ortaya çıkarılması ve buna bağlı olarak uygun önleyici tedbirlerin belirlenmesi amacıyla hasar türleri genel olarak şu biçimde gruplandırılabilir: distorsiyon ve deformasyonlar, korozyon, sürünmeye bağlı hasarlar, aşınma, yorulma, imalat aşamasından kaynaklanan hatalar (döküm, metal dışı kalınlı, ısıl işlem,

hadde, montaj). Bu tür hasarlar, farklı temel hasar mekanizmalarını içermekte olup, pek çok durumda iki veya daha fazla mekanizmanın aynı hasar üzerinde eşzamanlı olarak etkili olabileceği de göz önünde bulundurulmalıdır [5].

- Hasar Analizi ve Aşamaları

Hasar analizi, bir bileşen ya da sistemde meydana gelen hasarın nedenlerini ortaya koymak amacıyla hasara ilişkin bulguların sistematik biçimde toplanması, değerlendirilmesi ve yorumlanmasının yanı sıra sonuçların raporlanmasını içeren kapsamlı bir inceleme sürecidir. Bu süreç sayesinde hasarın oluşum mekanizmaları ayrıntılı olarak anlaşılır ve benzer türdeki arızaların gelecekte ortaya çıkmasını engellemek için gerekli mühendislik önlemlerinin belirlenmesi mümkün olur. Ayrıca yürütülen hasar analizi çalışmaları ile sistemlerin ve ürünlerin kalite düzeyindeki gelişmeler izlenebilir ve üretim süreçlerine yönelik iyileştirmeler takip edilebilir [6].

Hasar analizi ile elde edilen bulgular doğrultusunda, benzer yapılar veya sistemler için gelecekte yürütülecek tasarım, imalat ve kalite kontrol faaliyetlerinde aynı tür hasarların tekrar oluşmasını engelleyecek mühendislik tedbirlerinin geliştirilmesi amaçlanır. Bu yönüyle hasar analizi, yalnızca mevcut bir arızanın nedenlerini ortaya çıkarmakla kalmayıp aynı zamanda üretim süreçlerinin ve tasarım yaklaşımlarının iyileştirilmesine katkı sağlayan önemli bir geri bildirim mekanizması işlevi görür [4].

Her ne kadar uygulanacak inceleme basamakları hasarın niteliğine, yayılma biçimine ve meydana geldiği çalışma koşullarına bağlı olarak değişiklik gösterebilse de hasar analizi genel olarak Şekil 1'de de özetlenebileceği belirli temel aşamalar çerçevesinde yürütülür. Bu temel adımlar şu şekilde özetlenebilir [7]:

1. **Hasarın net biçimde tanımlanması:** Hasarın kapsamı, şiddeti, oluşan deformasyon türü ve etkilediği bileşenlerin net olarak ortaya konulması.

2. **Geçmişe yönelik bilgi toplanması ve uygun numunelerin seçilmesi:** Üretim kayıtları, kullanım koşulları, bakım geçmişi gibi verilere ulaşılması ve incelemeye esas teşkil edecek örneklerin belirlenmesi.

3. **Hasarlı elemanın ön incelemesi:** Parçanın makro düzeyde gözlemlenmesi, yüzeydeki bozulmaların değerlendirilmesi ve sonraki analizler için gerekli hazırlıkların yapılması.

4. **Hasarlı parçaların ayrıntılı analizi:** Mikroskobik incelemeler, mekanik testler, kimyasal analizler ve gerekli diğer mühendislik yöntemleri aracılığıyla hasarın mekanizmalarının belirlenmesi.

5. **Elde edilen bulguların değerlendirilmesi, yorumlanması ve nihai hasar raporunun oluşturulması:** Analiz sonuçlarının bütüncül bir yaklaşımla yorumlanarak hasarın asli nedeninin ortaya konulması ve çözüm önerilerinin raporlanması.



Şekil 1. Hasar Yolu ve Hasar Analizi Yolu [4]

1.2. Kaynaklı Bağlantılarda Hasar Analizi

Literatürde gerçekleştirilen incelemelerin önemli bir bölümünde, kaynaklı birleştirmelerde ortaya çıkan hasarların temel nedeninin, çoğunlukla uygulanan kaynak işlemi sırasında yapılan hatalar ile ana malzeme ve kaynak metali arasındaki uyumsuzluklardan kaynaklandığı ifade edilmektedir. Kaynak bölgesinde meydana gelen bu tür uyumsuzluklar; metalurjik yapı farklılıkları, ısı girdisinin uygun kontrol edilememesi, soğuma hızındaki dengesizlikler ve kaynak metali ile esas malzemenin mekanik veya kimyasal özelliklerinin birbiriyle örtüşmemesi gibi çeşitli faktörlerin birleşimiyle ortaya çıkmaktadır. Bu durumun en belirgin sebeplerinden biri ise kaynağın geometrik tasarımına ilişkin değişkenlerin çok geniş bir aralıkta bulunması ve uygulamada bu parametrelerin gereksinimlere uygun şekilde seçilememesidir. Kaynak dikişinin şekli, kaynak hazırlığı, alın veya köşe birleşim geometrileri, nüfuziyet derinliği ve ısı girdisi gibi tasarımsal unsurlardaki yanlış seçimler; birleştirme bölgesinde gerilme yığılmalarına, düzensiz mikro yapıya ve nihayetinde hasara zemin hazırlayan zayıf bölgelerin oluşmasına neden olabilmektedir. Dolayısıyla, kaynak parametrelerinin doğru belirlenememesi yalnızca uygulama hatalarına yol açmakla kalmayıp, aynı zamanda kaynak bölgesinin bütünlüğünü ve uzun dönem performansını olumsuz etkileyen kritik bir unsur hâline gelmektedir [8,9].

Kaynaklı birleştirmelerde gerçekleştirilen hasar analizi genel olarak iki temel aşamadan oluşmaktadır. İlk aşama, hasarın kaynağını belirlemeye yönelik olarak hasarlı bölgenin ayrıntılı biçimde incelenmesini ve parçanın karakteristik özelliklerinin ortaya konulmasını içerir. Bu aşamada amaç, hasara yol açan hatanın doğru bir şekilde tanımlanması ve söz konusu hatanın kaynaklı bağlantı bölgesinde hangi mekanizmalar sonucu ortaya çıktığının anlaşılmasıdır. Kaynaklı bağlantılarda hata nedenini belirlemek için öncelikle görsel muayene, ışık mikroskopisi, tahribatsız muayene yöntemleri ve diğer malzeme testleri dâhil olmak üzere hasar analiz tekniklerinden yararlanılır. Bunlara ek olarak, bağlantı noktasında oluşan gerilmelerin analitik olarak değerlendirilmesi ve gerekli durumlarda uygun numuneler üzerinden detaylı incelemelerin yapılması önem taşır [8].

İlk bulguların ardından, daha detaylı incelemeler için ışık mikroskobunun yanı sıra taramalı veya geçirimli elektron mikroskobu gibi ileri mikroskobik teknikler de kullanılabilir. Elektron mikroskobu, mikro yapıdaki ince detayların görünür hâle getirilmesi sayesinde çatlak başlangıç bölgeleri, tane sınırı davranışları, faz dağılımı ve malzeme homojenliği gibi kritik parametrelerin daha hassas bir şekilde değerlendirilmesine olanak sağlar. Mikroskobik analizlere ek olarak yapılan kimyasal kompozisyon incelemeleri, kaynak metali ile esas malzeme arasındaki farklılıkların belirlenmesinde ve hasarın oluşum mekanizmasının doğru

yorumlanmasında önemli rol oynar. Bu kapsamlı değerlendirmeler sayesinde hasar bölgesinin tam anlamıyla anlaşılması mümkün olmakta ve hasarın altında yatan temel sebepler bilimsel olarak güvenilir biçimde ortaya konulmaktadır [8,10].

Hasar analizi sürecinin ikinci aşaması, benzer hasarların gelecekte tekrar ortaya çıkmasını engellemek amacıyla yapılan değerlendirmeleri, elde edilen sonuçların bütüncül biçimde analiz edilmesini ve nihai hasar raporunun hazırlanmasını kapsamaktadır. Bu aşamada öncelikle hasarın açık, anlaşılır ve teknik olarak doğru bir tanımının yapılması gerekir. Hasar göstergeleri, hasarın temel nedeni ve hasarın gelişiminde rol oynayan mekanizma arasındaki ayrımlar net bir biçimde ortaya konulmalıdır [10]. Bu nedenle mevcut durumun tüm bileşenleri dikkatle değerlendirilerek olası hasar göstergeleri ile hasar mekanizmaları doğru şekilde tanımlanmalıdır.

Kaynaklı bağlantılarda bu aşamanın sağlıklı yürütülebilmesi için, birleştirmede hasara yol açabilecek kusurların kapsamlı biçimde bilinmesi gereklidir. Kaynaklı yapılarda hasar çoğu zaman aşırı yüklenme ile teknolojik hataların birlikte etkimesi sonucu oluşsa da, temel belirleyici etkenin teknolojik hatalar olduğu bilinmektedir. Bu nedenle, hasarın kökenini açıklığa kavuşturabilmek için parçada ortaya çıkan bozulmanın hangi teknolojik hata türüyle ilişkili olduğunun doğru biçimde tespit edilmesi zorunludur. Nitekim kaynaklı birleştirmelerde hasar, tek bir hatadan kaynaklanabileceği gibi birden fazla teknolojik hatanın eşzamanlı etkisiyle de meydana gelebilir [4,11].

Teknolojik hatalar genel olarak üç ana kategori altında incelenmektedir [12]:

1. **Tasarım kaynaklı hatalar** (tasarım kusurları ve yanlış malzeme seçimi),
2. **Üretim ve tesis aşamasında ortaya çıkan hatalar** (imalat ve montaj hataları),
3. **Uygun olmayan servis ve çalışma koşullarına bağlı hatalar**.

Bu hatalar, hasar türlerinden biriyle ya da birkaçıyla ilişkili olarak hasarın ortaya çıkmasına neden olabilir. Aşırı zorlanma dışında kalan tüm nedenler teknolojik hata kapsamında değerlendirilir. Dolayısıyla teknolojik hatanın doğru şekilde tanımlanabilmesi için, öncelikle hasarın başladığı bölgenin, yani hasarı başlatan kritik noktanın tespit edilmesi gerekmektedir [11].

1.3. İş Makinelerinde Kaynaklı Bağlantının Önemi

İş makineleri, yol, liman, baraj, kanal vb. Alt yapıların hazırlanması, her çeşit kazı, yükleme, kırma işlemlerinin yapılması gibi birçok alanda kullanılmaktadır. Çalışma alanları ve yaptıkları işe, performanslarına göre çok farklı modellere ayrılmaktadır [13].

İş makineleri çalışma koşulları gereği uzun süreli ve döngüsel yüklemelere maruz kalan ekipmanlardır. Bu tür makinelerde, nominal gerilme seviyelerini artırarak gerilme yığılmasına neden olabilen bağlantı detayları kullanılmaktadır. Özellikle yaygın bir şekilde tercih edilen köşe ve punta kaynakları, bu bağlantıların başında gelir. Ağır ve sürekli yüklemelere maruz kalan iş makinelerinde, söz konusu kaynak bölgelerinde çatlak başlangıcı ve ilerlemesi olağan bir durumdur. Bu nedenle, bu tür makinelerin tasarım sürecinde kaynaklı birleştirme noktalarında ortaya çıkabilecek yorulma ve kırılma mekanizmalarının dikkatle değerlendirilmesi büyük önem taşımaktadır.

Derleme niteliğindeki bu çalışmada iş makinelerinde meydana gelen genel hasar türleri, hasar mekanizmaları, literatürde belirtilen örnek vakalar ve bu hasarların önlenmesine yönelik öneriler detaylı biçimde ele alınmıştır.

2. ESKAVATÖRLERDE GENEL HASAR TÜRLERİ VE NEDENLERİ

Ekskavatör tipi iş makinelerinde karşılaşılan hasarlar; tasarım, üretim, servis koşulları, kaynak bağlantı kalitesi ve kusurlarının etkisiyle ortaya çıkar. Bilindiği gibi, uygulanan yük birçok faktöre bağlı olarak değişkendir ve bu durum, kritik noktalarda tespit edilen yüksek gerilim yoğunlaşmasıyla birlikte, yapı yıkım sürecini anlamanın anahtarı haline gelir. Kırılma meydana geldiğinden, çatlak başlangıcının bir çentiğe nasıl aktarıldığı çok önemlidir; bu da ekskavatörün yapısındaki yük aktarımının kötü bir tasarıma sahip olduğunu gösterir. Böylece, uygulanan yük ve gerilim dağılımının kırılma mekanizması üzerindeki etkileri büyük önem taşımaktadır [14].

Ekskavatör tasarımının önemli bir yönü, kaynaklı çelik yapıların yorulma ve kırılma davranışıdır [15,16,17]. Üretimden kaynaklanan kusurlar ve heterojen mikro yapı (ana metal, kaynak metali, ısının tesiri altındaki bölge- ITAB) nedeniyle kaynaklı bağlantılar, çatlak başlangıcı ve büyümesi açısından en kritik parçalardır ve iş makinelerinde olduğu gibi değişken yükleme ve yorulmaya maruz kaldıklarında özel dikkat gerektirir [14].

Gerçekten de yorulma hasarının, bir makinenin hizmet ömrü boyunca meydana gelen arızaların yaklaşık yüzde seksenini (%80) oluşturduğu tahmin edilmektedir.

2.1. Yorulma

Yorulma hasar türü, tekrarlı yüklemelere maruz kaynaklı makine parçalarında ve/veya yapılarda oluşan hasarların birincil nedenidir. Hasar analizleri sonuçlarından, imal edilen çelik yapılarda yorulma çatlağının çoğu kez gerilim yığılmasının yüksek olduğu çentik etkisine sahip kaynak geometrilerinden başladığı anlaşılmıştır. Ayrıca gerilim yığılmasının oluştuğu noktaların dışında, bağlantının yorulma özelliklerine etkileyen çok sayıda faktör bulunduğundan kaynak bağlantısı ana metale göre daha düşük yorulma dayanımına sahiptir. Kalıntı çekme gerilmesinin büyüklüğü, ısının tesiri altındaki bölgenin (ITAB) mikro-yapısal etkisi diğer önemli parametreleri oluşturmaktadır. Kaynak bağlantısının yorulma özelliklerinin iyileştirilmesi, ITAB 'ın dayanımının toklukta düşüşe yol açmadan arttırılması, bağlantıdaki çekme kalıntı gerilmesinin ve çentik etkisinin azaltılmasıyla ilgili olduğu söylenebilir [18].

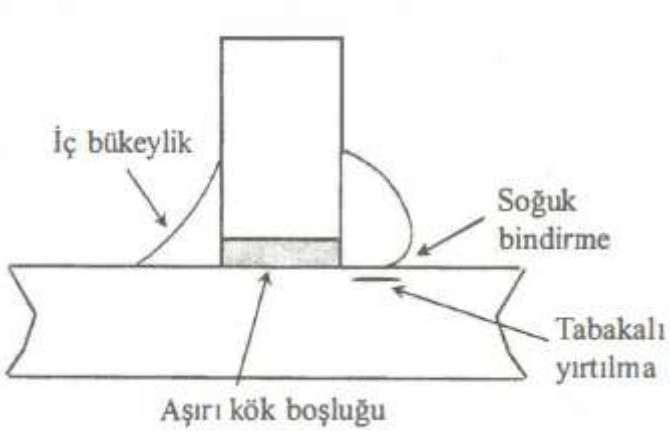
2.2. Aşırı Yükleme

Aşırı yükleme hasar türü genellikle parçanın çalışma şekli darbeli ve ani yüklemelere maruz olduğu şartlarda meydana gelmektedir. Hasar türünün isminden de anlaşılacağı üzere yapının aşırı yükleme şartlarında çalışma nedeniyle meydana gelir. Bu yükleme ve saha koşullarında çalışan parçalarda, malzemenin dayanımı tasarım aşamasında yeterince yüksek seçilmektedir. Diğer bir deyişle seçilen malzemenin darbe enerjisi ve eğme dayanımı yüksektir [6].

Malzemenin hesaplanan dayanım değerinin üzerinde bir gerilmenin oluştuğunda meydana gelen aşırı yükleme şartları ile zorunlu kırılma meydana gelmektedir. Bu tip kırılmalarda kırık yüzey incelemesinde gevrek kırılmadan ziyade ayrılma kırılması (zorunlu kırılma) türü, kırık yüzeyi tanecikli bir görünüş gösterir. Ayrılma veya zorunlu kırılma; plastik deformasyon oluşumu yerine atomlar arası bağların kopması şeklinde ortaya çıkmaktadır [6].

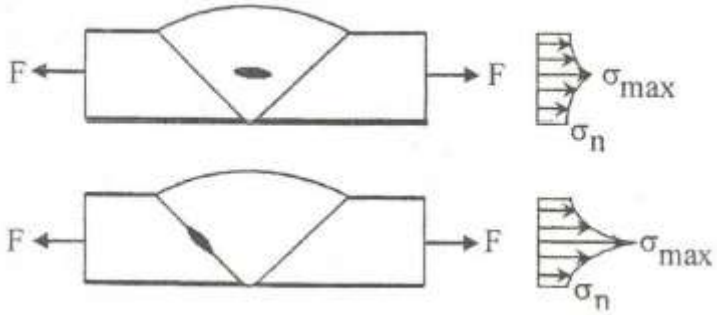
2.3. Kaynak Hataları

Kaynak hataları yerel gerilim yığılmasına ve kalıntı gerilmelere yol açabilmektedir. Genellikle bütün kaynaklı birleştirmeler farklı büyüklüklerde de olsa hata içermektedir. Kaynak prosesine ait değişkenlerin uygun seçilmemesi doğrudan ya da dolaylı olarak bağlantıda kaynak hatalarına neden olmaktadır [18]. Bu hatalar tek boyutlu ve düzlemsel olabildiği gibi farklı geometride hacimsel süreksizliklerden de oluşabilmektedir. Şekil 2 'de şematik olarak kaynak dikişi ve etrafında başlıca oluşabilecek kaynak hataları şematik olarak verilmiştir [19].



Şekil 2. Kaynak hataları ve gerilme yığılmasına yol açan diğer süreksizlikler [19].

Düzlemsel hata olarak göz önüne alabileceğimiz, hidrojen çatlağı, tabakalı yırtılma, nüfuziyet eksikliği ve katılaşma çatlağı, çatlak başlangıç noktalarını oluşturabilmektedirler. Hatanın konumu, büyüklüğü ve zorlanma altındaki kuvvet akış çizgilerinin yönlenmesi bağlantıda doğacak çentik etkisinin büyüklüğünü belirleyecektir (Şekil 3) [3].



Şekil 3. Kuvvet doğrultusunda ve çapraz konumdaki hatanın neden olduğu gerilme yığılması (şematik) [3].

3. LİTERATÜR TARAMASI

Bu bölümde, kaynaklı birleştirmelerde görülen hasar mekanizmaları ve bu hasarların analizi üzerine yapılan çalışmalar incelenmiştir. Literatür taraması, mevcut araştırmaların kapsamını, yöntemlerini ve elde edilen bulgularını ortaya koyarak bu çalışmanın bilimsel temelini oluşturmayı amaçlamaktadır.

Maury ve ekibi, hidrolik bir ekskavatör bomunda meydana gelen katastrofik kırılmanın nedenlerini araştırmak üzere kapsamlı bir hasar analizi gerçekleştirmiştir. Çalışmada, saha incelemeleri, tahribatsız muayeneler, makro ve mikro metalografik incelemeler, kimyasal analizler, sertlik ölçümleri ve sonlu elemanlar analizi gibi çok yönlü yöntemler kullanılmıştır. İnceleme sonucunda çatlağın, bom levhası ile man-hole plakasının birleştirildiği kaynak dikişi bölgesinde başladığı tespit edilmiştir. Kırık yüzeyindeki yorulma izleri (beach marks/ kumsal izleri) hasarın zaman içerisinde tekrarlı yükler altında geliştiğini göstermektedir [20].

Çalışmanın önemli bulgularından biri, bakım sürecinde sonradan eklenen man-hole plakasının malzeme özelliklerinin, ana taşıyıcı bom malzemesi ile tam olarak uyuşmadığıdır. Bu uyumsuzluk, bileşimin ve mikro yapının farklı olması nedeniyle bölgesel mekanik dayanımı düşürerek çatlak oluşumuna zemin hazırlamıştır. Bunun yanında, termal kesme sırasında plaka üzerinde oluştuğu düşünülen yüzey olukları ve düzensizliklerin giderilmeden kaynak işlemine

geçilmesi, bu bölgelerde belirgin gerilme yığılmalarına sebep olmuştur. İncelemelerde kaynak metalinde oksit ve cüruf kalıntısı bulunması, elektrot hazırlığı ve ön ısıtma/ara paso sıcaklığı kontrolünün yetersiz olduğunu ortaya koymaktadır. Bu durum, kaynak bölgesinde martensitik ve gevrek bir yapının oluşmasına ve tokluğun önemli ölçüde azalmasına yol açmıştır [20].

Sonlu elemanlar analizinden elde edilen sonuçlar, teorik olarak en yüksek gerilme bölgelerinin yapının başka noktalarında bulunmasına rağmen, gerçek kırılmanın düşük kaliteli kaynak bölgesindeki yerel kusurlar nedeniyle çok daha erken ortaya çıktığını göstermektedir. Yaklaşık 40.000 saatlik çalışma sonunda meydana gelen bu beklenmeyen kırılma, malzeme uyumsuzluğu, yüzey süreksizlikleri, yetersiz kaynak kalitesi ve uygun olmayan bakım-onarım uygulamalarının birleşik etkisiyle gelişen yorulma hasarının bir sonucu olarak değerlendirilmiştir.

Ferhan Fıçıcı ve çalışma arkadaşları, Hidromek 220LC-2 model ekskavatörün bomu için parametrik bir üç boyutlu sonlu elemanlar modeli oluşturulmuş ve bom üzerindeki kritik bölgelerdeki gerilme dağılımları detaylı bir şekilde incelenmiştir. Araştırmacılar, özellikle kaynaklı bölgelerdeki gerilim yoğunlaşmalarının, yorulma çatlaklarının temel nedeni olduğunu bildirdi. Geliştirilen model aracılığıyla bomun çeşitli noktalarında eşdeğer Von Mises gerilmeleri hesaplanmış ve bu bölgelerdeki gerilme seviyeleri dikkate alınarak Goodman kriteri ile yorulma ömrü tahminleri yapılmıştır [21].

Tablo 1. Çevrim Sayıları [21]

		1	2	3	4
Se = 47 MPa	N	172573	308987	217660	251934
Se = 53 MPa	N	227144	419529	290057	338360

Tablo 1'de elde edilen çevrim sayıları ekskavatör bomu alt sacının kalınlığı 3mm arttırılarak tekrar hesaplanmıştır. Yeni sac kalınlığı için elde edilen değerler ve çevrim sayısındaki yüzde artış Tablo 2'de verilmiştir [21].

Tablo 2. Çevrim Sayıları ve Ömürde Yüzde Artışlar [21]

		1	2	3	4
Se = 47 MPa	N	176518	334554	285846	325743
	Yüzde Artış	2,29%	8,27%	31,33%	29,30%
Se = 53 MPa	N	232617	456173	386500	443527
	Yüzde Artış	2,41%	8,73%	33,25%	31,08%

Bu tabloda da görülebileceği gibi sac kalınlığındaki artış ile %2,29'luk bir ömür artışı elde etmek mümkün olmaktadır. Bu sonuç, küçük tasarım değişikliklerinin bile yorulma dayanımını önemli ölçüde etkileyebileceğini göstermektedir [21].

M. Bošnjak ve arkadaşları bir tekerlekli ekskavatörün (BWE) kovasında meydana gelen hasarın incelemesini gerçekleştirmiştir. Araştırma kapsamında malzeme özelliklerini analiz etmek için kimyasal analiz testleri, sertlik ölçümleri ve gerinim ölçümü gibi deneysel testleri içeren bir hasar analizi metodolojisi yolu izlenmiştir. Ardından bu deneysel veriler farklı yük koşulları altında kepçe üzerindeki gerilim durumlarını hesaplamak üzere Doğrusal

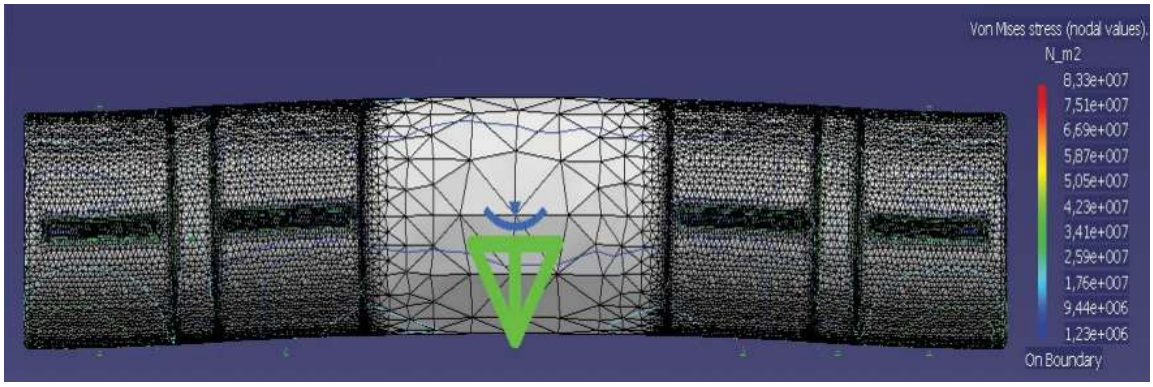
Sonlu Elemanlar Yöntemi (LFEM) ile birleştirilmiştir. Çalışmada hasara neden olan mekanizmaları belirlemek amacıyla deneysel olarak belirlenen çalışma ve kalıntı gerilmelerin üst üste bindirilmesi ve toplam asal gerilmelerin hesaplanması yaklaşımı kullanılmıştır. Elde edilen veriler sonucunda hasarın; hatalı malzeme seçimi ve kusurlu geometrik şekillendirme gibi tasarım kaynaklı hatalardan meydana geldiği gözlemlenmiştir. Bununla birlikte yapıda bulunan kalıntı gerilmeler ve kaynakta bulunan soğuk çatlaklar gibi üretim kaynaklı hatalar da yorulma çatlaklarının oluşmasına ve beraberinde ekskavatör kovalarının hasara uğramasına neden olmuştur [22].

A. Öndürücü ve Ö. Kandbir, bir greyderin dişli rotunda meydana gelen hasarın nedenini araştırmıştır. Hasarlı parçanın kimyasal analizi gerçekleştirilmiş ve malzeme bilgisi **St52 (S355) çeliği** olarak belirlenmiştir. Malzemenin mekanik özelliklerini belirlemek amacıyla sertlik, çentik darbe ve üç nokta eğme testleri gerçekleştirilmiştir. Metalografik incelemeler optik mikroskop ve Taramalı Elektron Mikroskobu (SEM) ile gerçekleştirilmiş, kırılmanın sünek kırılma yapısı gösterdiği gözlemlenmiştir. Parçanın ayrıca sonlu elemanlar modeli oluşturularak analizi yapılmıştır. Analizler sonucunda, parçanın hasara uğramasının temel nedeni olarak çalışma şartları nedeniyle aşırı zorlanma ve darbe yüklemesi olarak belirlenmiştir. Meydana gelen kırılmanın ise malzeme dayanımının üzerinde bir gerilme oluşması sonucu meydana gelen Ayrılma kırılması veya zorunlu kırılma olduğu ve hasarın gerilim yığılmasının beklendiği birleşme noktasında gerçekleştiği görülmüştür [6].

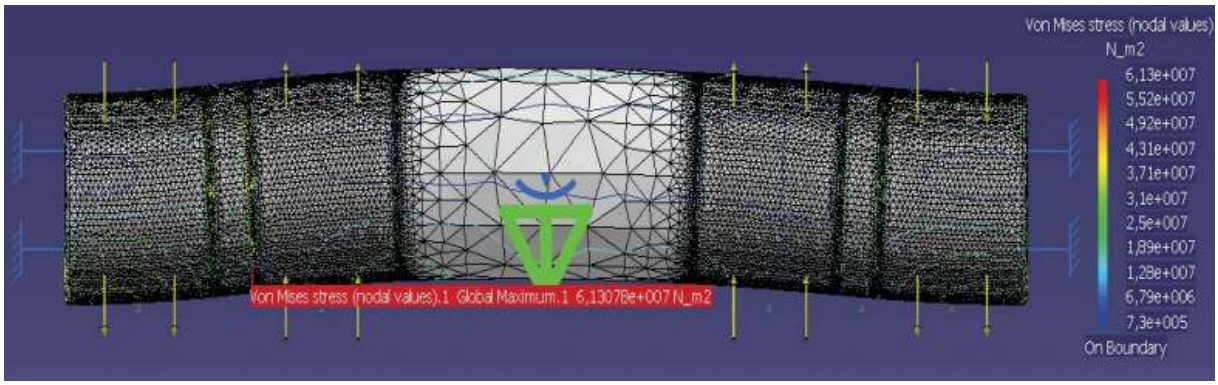
M. Makaracı ve çalışma arkadaşları, direksiyon sisteminin önemli parçası olan direksiyon aksonunun statik yükler altındaki davranışını incelemiştir. Bu çalışmada 3 boyutlu geometriye sahip akson modeli ile aksonun gerilme analizleri, darbe yükü, acil frenleme ve kaygan zemin koşulları gibi zorlu saha çalışma senaryolarında Sonlu Elemanlar Metodu (FEM) kullanılarak gerçekleştirilmiş. Malzeme olarak QT500-7 küresel dökme demir kullanılmıştır. Analizlerin sonucunda ise en yüksek gerilmenin malzemenin akma mukavemeti olan 320 MPa değerinin altında olduğu ve statik olarak bu durumun güvenli olduğu tespit edilmiştir. Bununla birlikte araştırmacılar asıl hasarın yorulma sonucunda gerçekleşebileceğini belirtmiş olup bu nedenle de yorulma testinin de yapılmasının gerekliliğini belirtmiştir [23].

Dudziński ve arkadaşları, çalışmalarında bir ekskavatörün bom süspansiyonunda meydana gelen hasarın kök neden analizini gerçekleştirmiştir. Bu hasar makinenin performansında ciddi aksamalara ve uzun süreli hizmet dışı kalmaya bağlı oldukça yüksek finansal kayıplara neden olmuştur. Gerçekleştirilen metalografik incelemeler ve Sonlu Elemanlar Yöntemi (FEM) ile analizlerle hasarın üç faktörün birleşimi sonucu oluşan bir yorulma kırılması olduğu ortaya konmuştur. İlk olarak aksın malzemesinin, nicel olarak yüksek yüklere maruz kalan taşıyıcı yapılar için uygun olmayan, Widmanstätten yapısına sahip homojen olmayan ferritik ve perlitik bir mikroyapı sergilediği görülmüştür. Bu durum temin edilen malzemenin, analiz bilgilerini içeren sertifikasındaki gereksinimleri karşılamadığını refere etmektedir. İkinci olarak yorulma çatlağının başlama noktasının, eksende bir yapısal çentik üzerinde olduğu belirlenmiştir ek olarak deforme olmuş bir segmanının ek eğilme kuvvetleri oluşturarak kırılma bölgesinde gerilim konsantrasyonunu artırdığı da görülmüştür. Bu durum ilgili bölgede akma mukavemetini aşan düşük çevrimli yorulma gerilimine yol açmıştır. Son olarak ise makine üzerinde gerçekleştirilen deneysel ölçümler, maksimum yüklerin teorik tasarım yüklerinden %18 daha yüksek olduğunu göstermiştir. Düzeltici aksiyon olarak, aksın tasarımının tamamen yeniden düzenlenmesi gerçekleştirilmiş ve uygun Widmanstätten yapısı içermeyen mikroyapıya sahip 40HM çeliği kullanılmıştır. Bunun sonucunda tasarım FEM ile doğrulanmıştır ve maksimum gerilimlerin malzemenin yorulma mukavemeti sınırının altında kaldığını ve mukavemetini önemli ölçüde arttırdığı raporlanmıştır [24].

Demiralp ve Türkeş, gerçekleştirdikleri çalışmalarında bir ekskavatörün kova-arm bağlantısını sağlayan SAE 8620 çeliğinden imal edilen piminin yorulma dayanımını üç boyutlu sonlu elemanlar modeli ile incelemiştir. Pim üzerindeki kanallar yağlamanın daha sağlıklı yapılması için açılmışken çentik etkisi göz önüne alınmamıştır. Yağlama kanalları (Şekil 4) pimin ömrünün daha kısa olmasına ve yorularak kırılmasına yol açmaktadır. Başka bir deyişle, yağlama kanalları pimin ömrünü kısaltmakta ve yorulma kırılmasına neden olmaktadır. Araştırmacılar yeni bir tasarımla yağlama kanallarını kaldırarak düz pim tasarımı yapmış (Şekil 5), aynı koşullar altında analizi tekrarlayarak sonucunda pim üzerindeki en yüksek gerilimin üçte bir değerinde düşüş gerçekleştiğini gözlemlemiştir. Pim üzerindeki kanallar burca taşınarak yağlama görevini meydana getirmesi sağlanmış olup yorulma ömrü artmıştır. Her iki makine de aynı arazi koşullarında çalıştırıldığında, kanallı pimli ekskavatör on bir bin (11.000) saatlik çalışmadan sonra yorulma nedeniyle kırılırken, düz pimli ekskavatör on sekiz bin (18.000) saatlik çalışmadan sonra yorulma nedeniyle kırılmaktadır. Ayrıca düz pim üretiminin hem kolay hem de uygun maliyetli olduğu belirtilmektedir [25].



Şekil 4. Kanallı Pim Üzerindeki Eşdeğer Gerilmeler [25]



Şekil 5. Düz Pim Üzerindeki Eşdeğer Gerilmeler [25]

-Hasar Önleme Çareleri

İş makinelerinde meydana gelen hasarın doğru analiz edilmesi ve proaktif yaklaşımların benimsenmesi hem makinenin performans verimliliği için hem de ekonomik kayıpların en aza indirilmesi için günümüzde önemini korumaktadır. Mevcut durumda iş makinelerinin ve makine parçalarının kullanım ömrünü uzatmak ve meydana gelebilecek hasarları mümkün olan en temel aşamada tespit etmek hasarın büyümeden önlenmesi yaklaşımıdır.

Parçalarda oluşan hasarların tamamen önlenmesi mümkün olmasa da iş makinelerinde özellikle kaynaklı bağlantılarında meydana gelen hasarların önüne geçmek için tasarım, üretim ve işletme aşamalarında mühendislik aksiyonları alınmalıdır [5]. Kaynaklı birleşimlerde hasarın

temel nedeni, çoğunlukla uygulanan kaynak işlemi sırasında yapılan hatalar ile ana malzeme ve kaynak metali arasındaki uyumsuzluklardan kaynaklandığı görülmektedir.

Bu tür hataların ve hasarların önlenmesi için, her bir birleşim için uygun Kaynak Prosedür Şartnamesi (WPS) hazırlanmalıdır. Kaynak işlemi sonrası Tahribatsız Muayene (NDT) gerçekleştirilmelidir. Ayrıca kritik olarak belirlenen kaynak bölgelerinde nüfuziyet kontrolü, uygun ısı girdisi ve paso arası sıcaklık kontrolü uygulanmalıdır. Isı girdisinin uygun kontrol edilememesi ve soğuma hızındaki dengesizlikler metalurjik yapı farklılıklarına yol açar [20]. Kaynak parametreleri, malzeme mikro yapısını kontrol edecek şekilde optimize edilmelidir ve Isının Tesiri Altındaki Bölge (ITAB) genişliği ve sertlik dağılımı düzenli olarak ölçülmelidir.

Tasarım aşamasında malzemenin dayanımı, özellikle darbe enerjisi ve eğme dayanımı yüksek olacak şekilde yeterince yüksek seçilmelidir. Hasara neden olan hatalı malzeme seçimi ve kusurlu geometrik şekillendirme gibi tasarım kaynaklı hatalardan kaçınılmalıdır [6]. Bakım onarım sürecinde eklenen parçaların malzeme özelliklerinin, ana malzeme ile tam olarak uyuşmaması nedeniyle bu uyumsuzluk bölgesel dayanımı düşürerek çatlak oluşuma yol açar [20].

Tasarımsal unsurlardaki yanlış seçimler (kaynak dikişinin şekli, nüfuziyet derinliği vb.) gerilim yığılmalarına ve mukavemet açısından zayıf bölgelere neden olabilir. Yağlama kanalları gibi çentik etkisi yaratan detaylar, pimin ömrünü kısaltıp yorulma kırılmasına neden olabilir; bu kanalların burca taşınması gibi tasarımsal çözümler yorulma ömrünü önemli ölçüde artırmıştır. (11.000 saatten 18.000 saate çıkış) [25].

4. SONUÇ

Bu derleme çalışmasında literatürde bulunan çalışmalar kapsamında iş makinelerinde işletme şartlarında karşılaşılan başlıca hasar türleri, hasarların oluşum nedenleri ve önleyici öneriler alt başlıklar halinde değerlendirilmiştir. Yapılan araştırmalar, iş makinelerinde meydana gelen hasarların önemli bir kısmının kaynaklı bağlantı esaslı olduğunu kaynaklandığını göstermektedir. Özellikle ekskavatör tipi iş makinaları yoğun dinamik yükler, darbeli zorlanmalar ve zorlu çevresel koşullar altında çalışan kritik yapısal elemanlardır.

Literatür verileri ekskavatör bomları, bağlantı noktaları ve benzeri konstrüksiyon parçalarında görülen hasarların çoğunlukla kaynak nedeniyle yorulma çatlaklarından kaynaklandığını ortaya koymaktadır. Yorulma hasarı, tekrarlı yüklemelere maruz kalan kaynaklı makine parçalarında birincil hasar nedenidir. Tahminlere göre, bir makinenin hizmet ömrü boyunca meydana gelen arızaların yaklaşık yüzde sekseni (%80) yorulma hasarından oluşmaktadır.

Hasarlar genellikle tasarım kaynaklı hatalar (yanlış malzeme seçimi, tasarım kusurları), üretim ve tesis aşamasında ortaya çıkan hatalar (kaynak proses hataları, eksik nüfuziyet, cüruf kalıntıları) ve uygun olmayan servis koşullarına bağlı hatalar (aşırı zorlanma, yetersiz bakım) gibi teknolojik hataların birleşimi sonucu ortaya çıkmaktadır.

Hasar analizleri, imal edilen çelik yapılarda yorulma çatlağının çoğunlukla gerilim yığılmasının yüksek olduğu çentik etkisine sahip kaynak geometrilerinden başladığını göstermiştir. Kaynaklı bağlantılar, yük aktarımında yüksek gerilim yığılmalarına yol açarak, zamanla servis şartlarındaki yüklemelere rağmen hasar oluşturabilmektedir.

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KIYI VE AÇIK DENİZ RÜZGÂR TÜRBİNİ TİPLERİ VE MODELLENMELERİ

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ÖZET

Rüzgâr enerjisi, sürekli olarak kullanılan en eski yenilenebilir enerji kaynakları arasında yer almaktadır. Günümüzde karasal rüzgâr türbinlerinin kurulu gücü dünya genelinde 944 GW'ı geçmiştir. Ancak sürekli artan enerji talebi ve rüzgâr enerjisi yönünden zengin karasal alanların sınırlı oluşu, kıyı ve açık denizlerde kurulan deniz üstü rüzgâr türbinlerine yönelimi hızlandırmıştır. Çünkü deniz üstü alanlar, karasal alanlara göre çok daha engelsiz ve rüzgâr enerjisi yönünden zengindir. Böylece daha düşük yüksekliklerdeki güçlü ve stabil rüzgâr hızlarından faydalanılabilmekte ve yıllık enerji verimliliği arttırılmaktadır. Denizin taban yapısına, su derinliğine, ve zorlu atmosferik-oşinografik koşullara bağlı olarak farklı taban ve temel tiplerine sahip deniz üstü rüzgâr türbinleri tercih edilmektedir. Denizde 50 metre derinliğe kadar olan bölgelerde sabit temel tipi oldukça ekonomik iken, derinliğin 50 metreyi aşan bölgelerde yüzer temel tipleri kullanılmaktadır. Yüzer temelli türbinler, derinlikten bağımsız olarak geniş alanlarda enerji üretimine imkan tanısa da ilk yatırım, karmaşık demirleme ve bakım maliyetleri sabit temelli tiplere göre daha yüksektir. Ayrıca yüzer tip türbinlerin fiziksel prototip testleri (rüzgâr tüneli, ölçekli saha deneyleri ve veri toplama altyapısı) çok yüksek maliyetlere sahiptir. Ancak, Hesaplamalı Akışkanlar Dinamiği (HAD) aracılığıyla, yapısal analiz, dalga-etkileşim modelleri ve kontrol sistemleri gibi çoklu fizik simülasyonları sanal ortamda gerçekleştirilerek, henüz tasarım aşamasında yüksek performanslı türbin modelleri belirlenebilmektedir. Böylece yüksek maliyetli test aşamasından kâr edilerek tasarım süreçleri hızlandırılmakta ve riskler önemli ölçüde azaltılmaktadır. Bu çalışmada, günümüzde literatürdeki test ve simülasyonlarla doğrulanmış model verilerinin makine öğrenmesi tekniğiyle işlenerek, belirli bir türbin tipinin tepki çıktısını veren matematik modelinin ve transfer fonksiyonunun oluşturulmasını sağlayacak algoritmanın geliştirilmesi ele alınmıştır. Böylece tasarım uzayı oldukça geniş modellerde bile çok kısa süreler içerisinde türbin performansı belirlenebilmekte ve fizibilite projesi aşamasındayken en ideal türbin modeli elde edilebilmektedir.

Anahtar Kelimeler: Deniz Üstü Rüzgâr Türbini, Türbin Modelleme, Makine Öğrenmesi, Tepki Fonksiyonu, HAD.

COASTAL AND OFFSHORE WIND TURBINE TYPES AND MODELLING

ABSTRACT

Wind energy is among the oldest continuously used renewable energy sources. Currently, the installed capacity of land-based wind turbines worldwide exceeds 944 GW. However, increasing energy demand and the limited availability of wind-rich land areas have accelerated the shift toward offshore wind turbines installed along coasts and offshore. Offshore regions are more open and have richer wind resources than onshore areas. This allows for the use of strong and stable wind speeds at lower heights, improving annual energy efficiency. Offshore wind turbines with different foundation types are chosen based on seabed conditions, water depth, and challenging weather and sea conditions. While fixed foundations are cost-effective in areas up to 50 meters deep, floating foundations are used in deeper waters. Floating turbines can generate energy over large areas regardless of depth, but they require a higher initial investment, complex mooring systems, and higher maintenance costs compared to fixed foundations. Physical prototype testing, including wind tunnel experiments, scaled field tests, and data collection infrastructure, is very expensive. However, using Computational Fluid Dynamics (CFD), it is possible to identify high-performance turbine designs during development through multi-physics simulations that include structural analysis, wave interaction models, and control systems in a virtual environment. This approach eliminates costly physical testing, accelerates the design process, and significantly reduces risks. In this study, the development of an algorithm that generates the mathematical model and transfer function providing the response output of a specific turbine type by processing model data validated through tests and simulations in the literature with machine learning techniques is discussed. This method allows for the assessment of turbine performance in very short timeframes, even for models with extensive design spaces. As a result, the optimal turbine model can be identified during the project's feasibility phase.

Keywords: Offshore Wind Turbine, Turbine Modelling, Machine Learning, Response Function, CFD.

GİRİŞ

Rüzgâr enerjisi, yenilenebilir enerji kaynakları arasında giderek artan bir öneme sahiptir ve küresel yeşil enerji dönüşümünün merkezinde yer almaktadır. Güncel verilere göre, dünya genelinde karasal rüzgâr türbinlerinin toplam kurulu kapasitesi 944 GW'ı aşmış durumdadır (Communication, 2024). Bununla birlikte, rüzgâr enerjisi bakımından zengin olan karasal bölgelerdeki uygun alanların sınırlı olması, yerleşim yoğunluğu ve artan enerji talebi, üretim altyapısının deniz ortamlarına taşınmasını zorunlu kılmaktadır. Bu nedenle, son yıllarda deniz üstü rüzgâr enerjisi teknolojileri hem araştırma hem yatırım alanında hızla öne çıkmıştır.

Deniz ortamında, rüzgârın karaya kıyasla daha istikrarlı, yüksek hızlı ve düşük türbülanslı olması, türbinlerin verimliliğini önemli ölçüde artırmaktadır. Rüzgâr akışının engellerle kesintiye uğramaması, enerji üretiminde sürekliliği ve istikrarı sağlar. Bu avantajlara karşın, deniz koşulları sistem tasarımı açısından yeni teknik zorluklar doğurmaktadır. Özellikle su derinliği, deniz tabanı özellikleri, akıntılar ve atmosferik etkiler, deniz üstü türbinlerin yapısal tasarımını ve işletme stratejilerini doğrudan etkilemektedir.

Deniz üstü rüzgâr türbinleri (DRES) genel olarak sabit temelli ve yüzer platformlu sistemler olarak iki temel sınıfta incelenmektedir. Sabit temelli sistemler genellikle 50 metreye kadar olan sığ denizlerde uygulanabilirken, derin sularda bu yöntem teknik açıdan sınırlı kalmaktadır. Bu tür ortamlarda yüzer türbin sistemleri, su derinliğinden bağımsız enerji üretimi sağlayarak önemli bir alternatif oluşturur. Bununla birlikte, yüzer platformlarda demirleme sistemleri, stabilite kontrolü ve bakım operasyonları gibi etkenler, sabit temelli sistemlere göre hem ilk yatırım hem de işletme maliyetlerini artırmaktadır. Türbin performansının henüz tasarım aşamasındayken optimize edilmesi, proje maliyetlerinin düşürülmesi ve sürdürülebilirlik açısından oldukça kritiktir.

Bu çalışmada amaç henüz fiziksel test veya prototip aşamasına gelmeden önce sayısal simülasyon temelli optimizasyon yöntemleriyle türbin performansının değerlendirilmesidir. Ayrıca hali hazırda literatürde test ve simülasyonlarla doğrulanmış model verilerinin makine öğrenmesi tekniğiyle işlenerek, belirli bir türbin tipinin tepki çıktısını veren matematik modelinin ve transfer fonksiyonunun oluşturulmasının gerekliliği bu çalışmada ele alınmıştır. Böylece tasarım uzayı oldukça geniş modellerin türbin performansı saniyeler içerisinde belirlenebilmekte ve fizibilite projesi aşamasındayken en ideal türbin modeli dakikalar içerisinde elde edilebilmektedir.

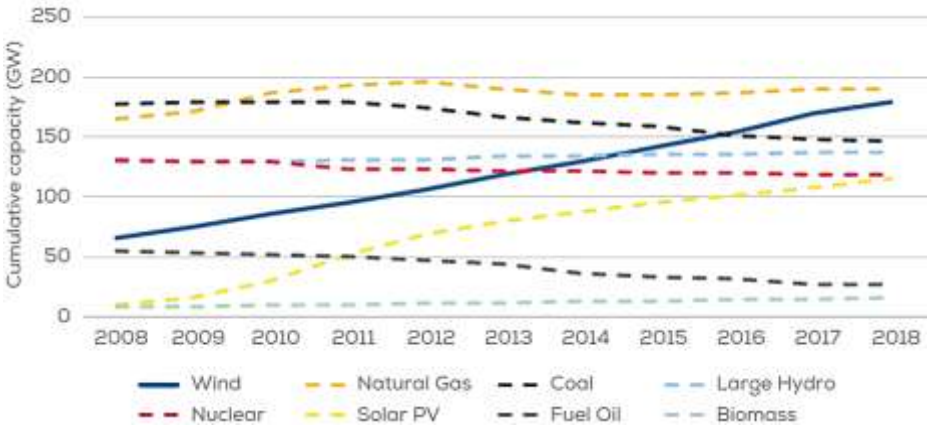
Küresel Ölçekte Rüzgâr Türbinleri

Rüzgâr enerjisi, küresel ölçekte enerji üretiminde hızla önem kazanan sürdürülebilir kaynaklardan biri haline gelmiştir. Artan çevresel kaygılar, fosil yakıtların tükenme riski ve karbon emisyonlarının azaltılması yönündeki politik hedefler, yenilenebilir enerjiye olan talebi her zamankinden fazla artırmıştır. Bu dönüşüm sürecinde rüzgâr enerjisi hem karadaki hem de denizdeki uygulamalarda geniş bir kullanım alanı bularak enerji dönüşümünün temel unsurlarından biri olmuştur.

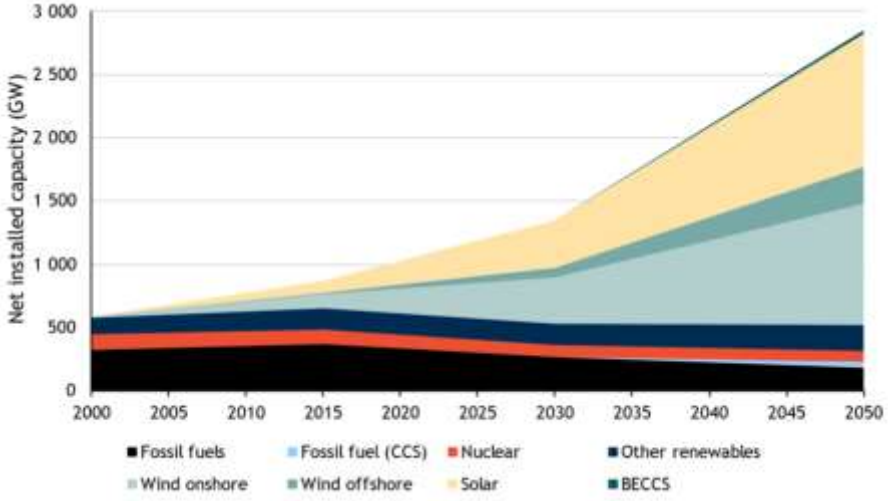
Teknolojik ilerlemeler, rüzgâr türbinlerinin aerodinamik verimini ve güç dönüşüm etkinliğini etkili oranda yükseltmiş, buna bağlı olarak enerji üretim maliyetleri geçmişe kıyasla belirgin şekilde azalmıştır. Ayrıca, uluslararası kurumlar ve devletler tarafından yürürlüğe konulan teşvik politikaları, yenilenebilir enerjiye geçiş sürecini hızlandırmıştır. Bu gelişmeler sonucunda, rüzgâr enerjisinin küresel enerji üretimindeki payı son on yılda sürekli artış göstermiştir. Şekil 1a'da, 2008–2018 yılları arasında Avrupa'da yenilenebilir enerji kaynaklarına dayalı kurulu güçteki değişim gösterilmektedir. Grafik, rüzgâr enerjisindeki artış trendinin gelecekte de süreceğini açık biçimde ortaya koymaktadır. Benzer bir projeksiyon da

Heflich vd. (2022) tarafından yapılmıştır. Özellikle "net sıfır emisyon" hedefi senaryosu kapsamında, yenilenebilir enerji kaynaklı kurulu güç kapasitesine göre 2050 öngörüsü Şekil 1b'de gösterilmiştir. Deniz üstü rüzgâr türbinlerinden elde edilecek enerjinin giderek artması, birim başına enerji maliyetlerinin de giderek azalması beklenmektedir.

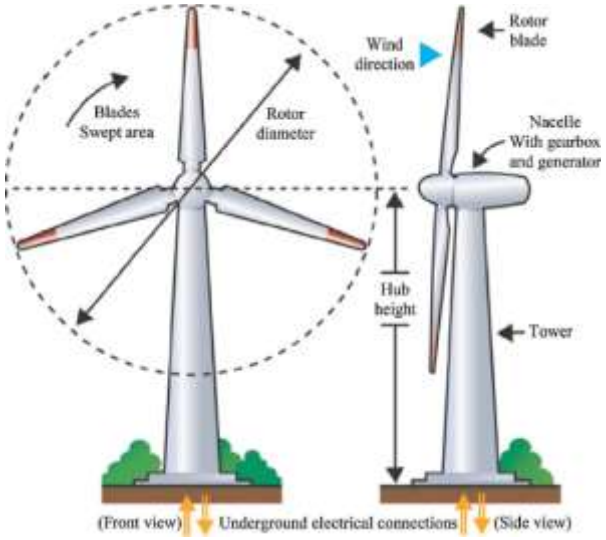
Rüzgâr enerjisinden elektrik üretimi, aerodinamik kuvvetleri elektrik enerjisine dönüştüren rüzgâr türbinleri aracılığıyla sağlanmaktadır (Şekil 2). Rüzgâr akımı, kanat profilleri üzerinden geçerken bir kaldırma kuvveti oluşturur ve bu kuvvet kanatların dönmesini sağlar. Kanatların oluşturduğu dönme momenti, rotor mili aracılığıyla jeneratöre iletilir; burada mekanik enerji elektrik enerjisine dönüştürülür. Üretilen elektrik, transformatörlerle gerilimi yükseltilerek şebekeye aktarılır. Günümüz türbinleri, rüzgâr yönü ve hızındaki değişimleri anlık olarak izleyen akıllı kontrol sistemleri ve gerektiğinde enerji depolama üniteleriyle birlikte çalışabilen hibrit yapıdadır (Terzioğlu vd., 2019).



Şekil 1a: Avrupa'da yenilenebilir enerji kaynaklı kurulu güç kapasitesinin 2008 yılından 2018 yılına kadar olan değişimi (Komusanac vd., 2019)



Şekil 1b: 2050 yılına kadar (net sıfır emisyon hedefi doğrultusunda), enerji kaynaklarına göre Avrupa Birliği'nin geleceğe yönelik net elektrik üretim kapasitesi tahmini (Heflich vd., 2022)



Şekil 2: Temel bir rüzgâr türbininin elemanları (Aminzadeh vd., 2023)

Rüzgâr türbinlerinden elde edilebilecek güç, esas olarak rüzgâr hızı ve kanatların tarama alanı ile ilişkilidir. Üretilen güç, hızın küpüyle orantılı olarak artar. Bu nedenle, rüzgâr hızının iki katına çıkması, enerji üretiminin yaklaşık sekiz kat artması anlamına gelir. Türbin kanat uzunluğu da üretim kapasitesinde belirleyici bir unsurdur; kanat yarıçapının büyümesiyle rotorun süpürdüğü alan artar ve daha fazla hava kütlesiyle etkileşim sağlanır. Rüzgâr enerjisinden elde edilen güç Denklem (1) ile ifade edilir:

$$P = \frac{1}{2}\rho A U_{\infty}^{3} C_p \qquad (1)$$

Burada,

P: Güç (Watt)

ρ: Hava yoğunluğu (kg/m^3)

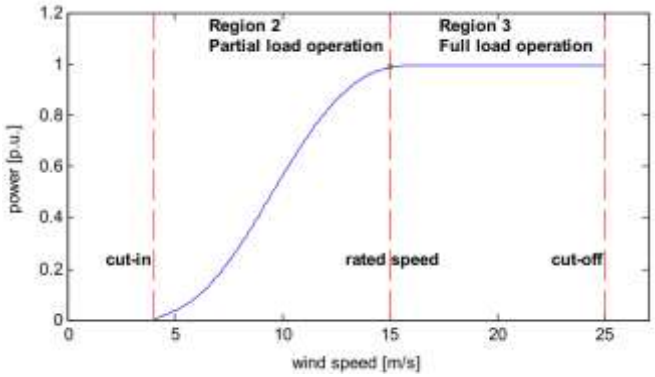
A: Pervanenin süpürdüğü alanı (m2)

U_{∞}: Rüzgâr hızı (m/s)

C_P: Güç katsayısı (Cp < 0,593 Betz kriter sınırı)

olarak ifade edilir. Bu bağıntı, rüzgâr türbininin teorik verim sınırını tanımlar ve türbinin tasarım parametrelerinin enerji üretim üzerindeki etkisini açık biçimde ortaya koyar.

Bir türbin yalnızca belirli rüzgâr hızı aralıklarında enerji üretimi yapabilir (Şekil 3). Türbinin çalışmaya başladığı en düşük hız olan genellikle 3–4 m/s “cut-in hızı” olarak adlandırılır. Bu hızın altında kanatların dönmesi için gerekli kinetik enerji oluşmaz. Rüzgâr hızı nominal (rated) değere ulaştığında (yaklaşık 12–15 m/s), türbin maksimum kapasitede çalışır. Bu değerin üzerindeki artışlar çıkış gücünü etkilemez; çünkü sistem bu noktada güç sınırlama moduna geçer. Cut-off hızı (yaklaşık 25 m/s) aşıldığında türbinin yapısal bütünlüğünü korumak ve servis ömrünü uzatmak için, türbin otomatik olarak durdurulur.

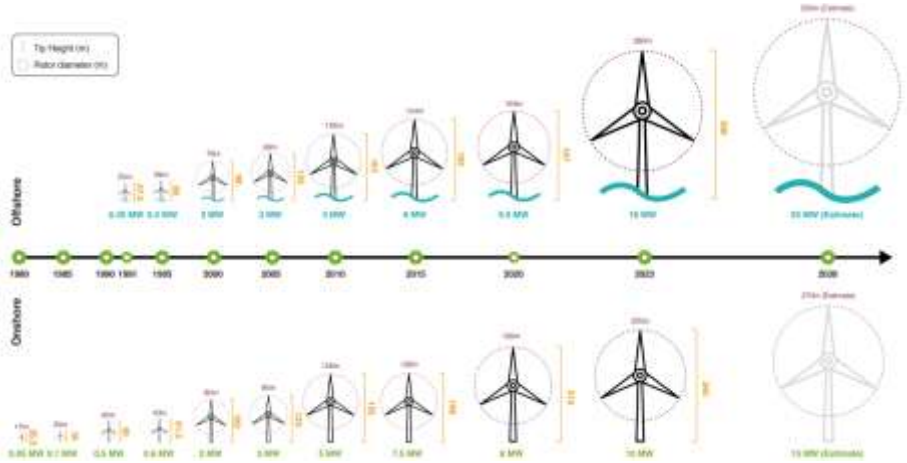


Şekil 3: Rüzgâr hızı ile türbin enerji çıkışı karakteristiği (Hall vd., 2010)

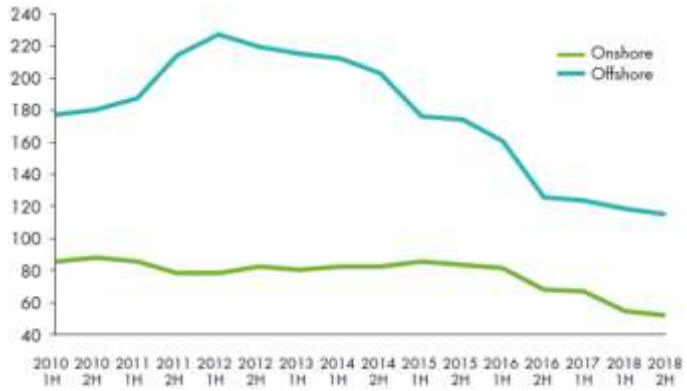
Rüzgâr hızının zamana göre istikrarlı olması, yani kaliteli rüzgâr koşullarının sağlanması, enerji üretiminde süreklilik açısından büyük önem taşır. Hızın ani değişim göstermemesi, türbin kanatları üzerindeki yükleri azaltır; böylece sistem daha kararlı çalışırken, sistemde oluşan mekanik yorulma değerlerinde azalma olur. Bu durum bakım aralıklarını uzatır ve işletme maliyetlerini düşürür. Aynı zamanda enerji üretimindeki kesintiler azaldığı için kapasite faktörü artar (Ünal vd., 2024).

Kara üstü türbinler, erişilebilirlik ve düşük yatırım maliyeti açısından avantajlıdır. Karada kurulum ve bakım operasyonları daha kolaydır; ayrıca uzun yıllara dayanan mühendislik birikimi sayesinde teknolojik olarak daha olgun bir yapıdadır. Ancak, karasal alanlarda rüzgâr potansiyeli genellikle düşüktür ve arazi pürüzlülüğü, binalar ve bitki örtüsü gibi engeller akış rejimini olumsuz etkiler. Bu nedenle türbin kulelerinin yüksekliği artırılmak zorunda kalınır. Ayrıca, görsel etki, gürültü ve arazi kullanımı gibi çevresel faktörler toplumsal kabulü zorlaştırabilir. Buna karşın, deniz üstü rüzgâr türbinleri daha düzenli (daha az türbülans, ortalama hızda daha az sapma) ve daha yüksek rüzgâr hızlarından faydalanır. Deniz yüzeyinin pürüzsüz sayılması nedeniyle daha düşük yüksekliklerde bile kaliteli rüzgâr koşulları elde edilebilir. Bu türbinler genellikle daha büyük boyutlarda tasarlanabilir ve birim türbin başına düşen üretim miktarı artar. Ayrıca, yerleşim alanlarından uzak oldukları için gürültü ve estetik kaygılar minimize edilir. Ancak bu avantajların yanında, deniz ortamında kurulum, bakım ve erişim maliyetleri çok daha yüksektir. Tuzlu suyun oluşturduğu korozyon, dalga yükleri ve erişim zorlukları türbinlerin ömrünü ve bakım gereksinimlerini doğrudan etkiler. Ayrıca, denizel ekosistem üzerindeki olası etkiler de dikkatle değerlendirilmelidir (Şentürk ve Oğuz, 2020).

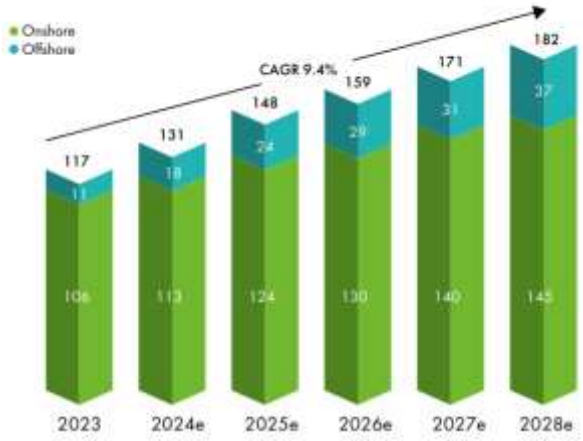
Son yıllarda düşen seyrüsefer ve kurulum maliyetleri, daha büyük rotor çapları ve gelişmiş malzeme teknolojileriyle birleşerek deniz üstü türbinlerin ekonomik açıdan giderek daha rekabetçi hale geldiğini göstermektedir. Şekil 4'te, 1980–2030 yılları arasında türbin boyutlarındaki gelişim; Şekil 5'te, türbin enerji maliyetlerinin zamana göre azalışı; Şekil 6'da ise 2024–2028 dönemi için kara ve deniz üstü türbinleri için kurulum beklentileri sunulmaktadır. Bu veriler, deniz üstü türbin teknolojilerinin gelecekte enerji sistemleri içinde daha baskın bir konuma yükseleceğini göstermektedir.



Şekil 4: Kara ve deniz üstü türbin büyüklükleri, 1980-2030 (Lee and Zhao 2024)



Şekil 5: Türbin başına (indirgenmiş) enerji maliyetinin tarihsel değişimi [$/MWh] (Ohlenforst vd., 2019)



Şekil 6: 2024-2028 yılları arasındaki kara ve deniz üstü için türbin kurulum beklentisi [GW] (Ohlenforst vd., 2019)

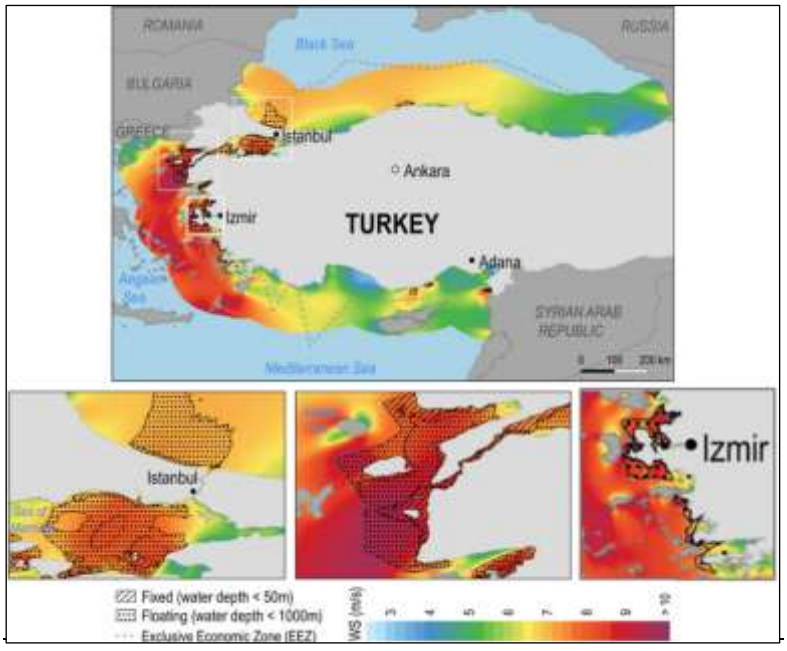
BULGULAR

Dünya Bankası'nın yayımladığı Going Global 2019 raporunda (Dutton vd., 2019), Türkiye'nin kıyı bölgelerinde dikkate değer bir deniz üstü rüzgâr enerjisi potansiyeline sahip olduğu vurgulanmıştır. Çalışmada özellikle Marmara ve Ege Denizi kıyılarının rüzgâr rejimi açısından uygun koşullar sunduğu, bu bölgelerin sabit ve yüzer tabanlı türbin teknolojileri için elverişli fırsatlar oluşturduğu belirtilmiştir. Ayrıca, Çanakkale Boğazı ve çevresindeki sığ deniz alanlarının, düşük maliyetli sabit temelli kurulumlara uygun olduğu ifade edilmiştir (Şekil 7).

Rüzgâr türbinlerinin kurulacağı alanlarda deniz derinliği önemli bir tasarım kriteridir. Türbinlerin güvenli ve uzun ömürlü çalışabilmesi için deniz tabanı koşullarına uygun temel tipinin seçilmesi gerekmektedir (Uzunoğlu vd., 2021). Temeller genel olarak sabit ve yüzer olmak üzere iki ana sınıfta incelenir (Şekil 8).

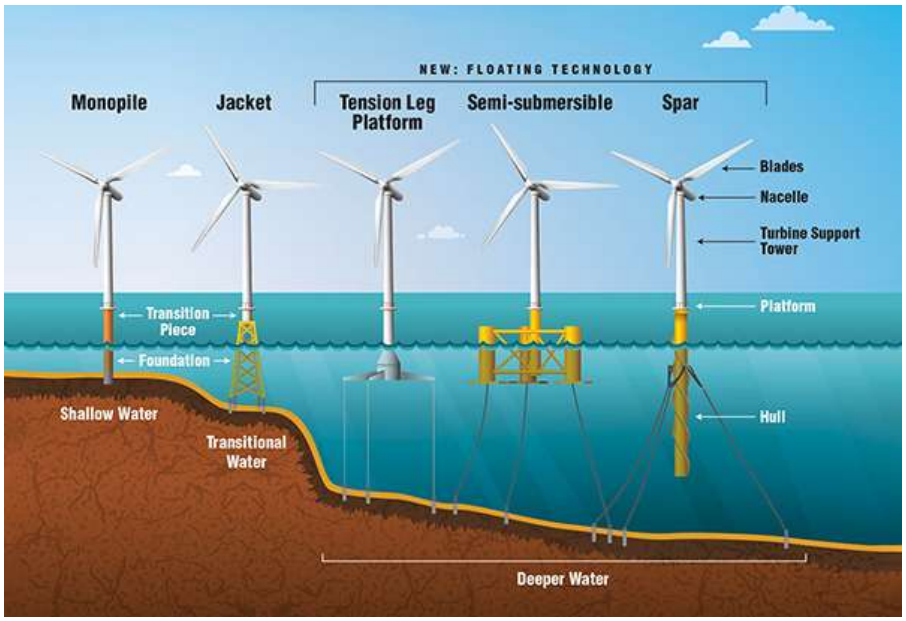
- 0–30 m derinliğe sahip sığ bölgelerde monopil temeller yaygın olarak kullanılır. Bu temeller, çelik boruların deniz tabanına çakılmasıyla oluşturulur ve düşük maliyetleriyle öne çıkar.
- 30–50 m aralığındaki orta derinliklerde ceket (jacket) tipi kafes yapılar tercih edilir. Dört ayaklı bu sistemler, yüksek stabilite sağlar ve zeminle geniş bir temas yüzeyi oluşturur.
- 50 m üzerindeki derin deniz koşullarında ise yüzer temeller (platformlar) kullanılır. Bu yapılar yüzeyde dengede kalır ve çelik halatlarla deniz tabanına demirlenir.

Doğru temel seçimi, yalnızca yapısal dayanıklılığı değil, aynı zamanda bakım sıklığını, ömür maliyetini ve enerji verimliliğini de doğrudan etkiler.



Şekil 7: Türkiye'de deniz üstü rüzgâr enerjisi potansiyelinin yüksek olduğu bölgeler -Dünya Bankası Raporu (Dutton vd., 2019)

Fizibilite çalışmalarında görüldüğü üzere, temel sistemi türbin maliyetinin en yüksek payına sahip bileşenlerden biridir. Yanlış temel seçimi, yatırım maliyetinin yükselmesine ve operasyon süresince performans düşüşüne neden olabilir.



Şekil 8: Deniz üstü rüzgâr türbinlerinde sabit ve yüzer tip temeller (Iraeta, 2021)

Yüzer platformlu türbinlerin ömrü, maruz kaldıkları rüzgâr, dalga ve akıntı yüklerinin dinamik karakterine doğrudan bağlıdır (Uzunoğlu vd., 2021). Bu kuvvetler, sistemde salınım, devinim ve eğilme momentleri oluşturarak türbin bileşenlerinde yorulma ve deformasyona neden olur. Bu nedenle, tasarım aşamasında doğal frekansın, çevresel yüklerin frekans aralığıyla çakışmaması büyük önem taşır; aksi durumda rezonans meydana gelir ve platform kararlılığı bozulur.

Hesaplama Modelleri

Fiziksel deneyler, türbin tasarımlarının güvenilir şekilde doğrulanması için en kesin yöntemdir. Rüzgâr tüneli testleri, dalga tankı deneyleri, HIL (hardware-in-the-loop) sistemleri ve çeşitli ölçekli yüzer platform deneyleri, aerodinamik ve hidrodinamik davranışların gerçek ortamda ölçülmesini sağlar. Özellikle uluslararası projelerde kullanılan OC3, OC4, OC5 ve OC6 benchmark modelleri, birçok deneysel veri seti sunarak sayısal modellerin doğrulanmasında standart haline gelmiştir. Ancak prototip testlerinin;

- Çok yüksek maliyetli olması,
- Büyük ölçekli test tanklarına ihtiyaç duyulması,
- Karmaşık kurulum süreçleri ve
- Testlerin tekrarlanmasının zor olması

gibi önemli dezavantajları bulunmaktadır. Bu nedenle deneysel veriler genellikle yalnızca kritik doğrulamalar için kullanılır ve geniş parametrik çalışmalar yerine temel referans niteliği taşır.

HAD (Hesaplamalı Akışkanlar Dinamiği) yaklaşımları, rüzgâr türbinlerinin aerodinamik ve hidrodinamik davranışını üç boyutlu ve yüksek çözünürlüklü akış çözücüleri ile incelemeye imkân tanır. Türbin kanatları etrafındaki sınır tabaka gelişimi, ayrılma bölgeleri, kanat uç girdapları, iz bölgesi (wake) oluşumu, platform hareketlerinin aerodinamik yüklere etkisi ve türbin–dalga etkileşimi gibi karmaşık fiziksel süreçler HAD-SEM (Sonlu Elemenlar Metodu) ortak simülasyonu ile ayrıntılı biçimde çözülebilir. Özellikle LES, DES, RANS gibi türbülans modelleri, hem sabit tabanlı hem de yüzer türbinlerin çalışma koşullarını modellemede önemli

rol oynar. Deniz üstü türbinlerin yüksek maliyetleri göz önüne alındığında, bilgisayar destekli simülasyonlar —özellikle HAD analizleri— fizibilite sürecinin temel bir bileşenidir. Bu sayısal analizler, türbinin aerodinamik ve hidrodinamik yükler altındaki davranışını öngörür ve fiziksel testlerin yerini büyük oranda alabilir. Böylece hem zamandan hem de prototip maliyetinden tasarruf edilebilir. Bir HAD simülasyonunda, performans değerlendirmesi şu temel kriterlere göre yapılır:

- Güç Üretimi: Türbinin farklı rüzgâr hızlarındaki enerji üretim kapasitesi, nominal hız aralığında verimliliğini belirler.
- Rezonans Analizi: Türbinin doğal frekansının dalga ve rüzgâr kaynaklı yüklerle etkileşimi kontrol edilerek yapısal güvenlik değerlendirilir.
- Stabilite ve Hareket: Platformun ileri-geri, yanal ve düşey hareketleri ile dönme, yalpa ve baş-kıç salınımı analiz edilir.

HAD analizleri yüksek doğruluk sağlamakla birlikte, çok yüksek hesaplama maliyetleri, uzun çözüm süreleri ve ağ yapısı (mesh) hassasiyeti gibi dezavantajlara sahiptir. Oldukça uzun hesaplama süreçleri, rüzgar enerjisi fizibilite projelerinin süresinin uzamasına ve böylece finansman sürecinde aksamalara sebebiyet vermektedir. Bu nedenle yalnızca kritik çalışma koşullarının detaylı incelenmesinde veya doğrulama aşamasında tercih edilir.

Deniz üstü rüzgâr türbinlerinin (DRES) aero-hidro-servo-yapısal davranışlarının modellenmesinde en yaygın yaklaşım, birden fazla fiziksel modülün zaman alanında eşzamanlı çalıştırıldığı entegre simülasyon çerçeveleridir. Bu kapsamda kullanılan OpenFAST, QBlade, MoorDyn, ElastoDyn, HydroDyn, AeroDyn, ServoDyn gibi açık kaynaklı yazılımlar; rüzgâr türbini tasarımında ihtiyaç duyulan çoklu fiziği düşük maliyetle ve yüksek esneklikle çözme imkânı sunmaktadır. Bu araçlar, türbinin tüm alt sistemlerini birbirine bağlı olarak çözer:

- Aerodinamik yükler, AeroDyn modülü ile BEM/UBEM tabanlı hesaplanır; kanat üzerindeki kaldırma/direnç kuvvetleri, açısal hız, TSR (Tip Speed Ratio – Kanat Uç Hızı) ve iz bölgesi etkileri zaman içinde takip edilir.
- Hidrodinamik davranışın analizinde, HydroDyn modülü ile Morison tabanlı kuvvetler veya potansiyel teori tabanlı çözüm uygulanır; platformun dalga etkisi altındaki hareketleri hesaplanır.
- Yapısal esnekliği belirlemek için, ElastoDyn modülü ile kule, rotor ve platformun elastik tepki özellikleri modellenir; özellikle yüzer türbinlerde eğilme-burulma momentleri bileşik etkisi kritik önemdedir.
- Kontrol sistemleri, ServoDyn modülü aracılığıyla, türbinin baş-kıç vurma ve dönme kontrolü ile jeneratör tork kontrolünü yönetir.
- Demirleme sistemi kapsamında, MoorDyn modülü ile zincirleme veya platform sabitleme hatlarının dinamik gerilme ve deplasmanları hesaplanır.

Bu açık kaynaklı çözümler, HAD'a kıyasla çok daha hızlıdır; dolayısıyla binlerce farklı deniz durumu, rüzgâr spektrumu, TSR değişimleri ve platform serbestlik dereceleri kısa sürede analiz edilebilir. Bu özellikleri sayesinde optimizasyon çalışmaları, parametrik taramalar ve erken tasarım değerlendirmeleri için ideal bir analiz altyapısı oluştururlar.

Açık kaynaklı aero-hidro-servo-yapısal analiz araçları, deniz üstü rüzgâr türbinlerinin bütüncül davranışını incelemek için yaygın biçimde kullanılmakla birlikte bazı temel sınırlamalara sahiptir. İlk olarak, aerodinamik modelleme çoğunlukla BEM/UBEM gibi yarı-ampirik yöntemlere dayanır ve bu yöntem tam HAD çözümlerine kıyasla daha basit olduğundan,

özellikle karmaşık akış ayrılmaları, iz bölgesi etkileşimleri ve yüksek TSR koşullarında doğruluk azalabilir. Hidrodinamik modellemeler ise genellikle potansiyel teori veya Morison denklemi gibi idealize yaklaşımlar kullanır; bu durum karmaşık platform geometrilerinde oluşan dalga yüklerinin, çarpma (slamming) etkilerinin ve türbülanslı akışların yeterince temsil edilememesine neden olabilir. Bunun yanı sıra, yapısal modeller çoğu zaman lineerleştirilmiş kiriş teorilerine dayanır ve yüksek deformasyon veya bağlantı bölgelerindeki karmaşık gerilme dağılımlarını tam olarak belirleyemez. Demirleme sistemlerinin modellenmesinde de benzer şekilde hatların akış kaynaklı titreşimleri, ani yük geçişleri ve malzemelerin doğrusal olmayan davranışları sınırlı oranda temsil edilir. Tüm bu alt modüller genellikle zayıf akuple (loosely coupled) şekilde çalıştığından, aerodinamik–hidrodinamik–yapısal–kontrol etkileşimi tam akuple çözümler kadar doğru sonuç üretmeyebilir.

Sonuç olarak bu açık kaynaklı modeller, kavramsal tasarım ve ön fizibilite çalışmaları için oldukça yeterli olsa da, detaylı yük kestirimi, karmaşık dalga koşulları veya tüm zaman serisi boyunca doğruluk gerektiren hassas mühendislik problemlerinde ek doğrulama veya daha yüksek doğruluğa sahip HAD–SEM analizleriyle desteklenmek zorundadır.

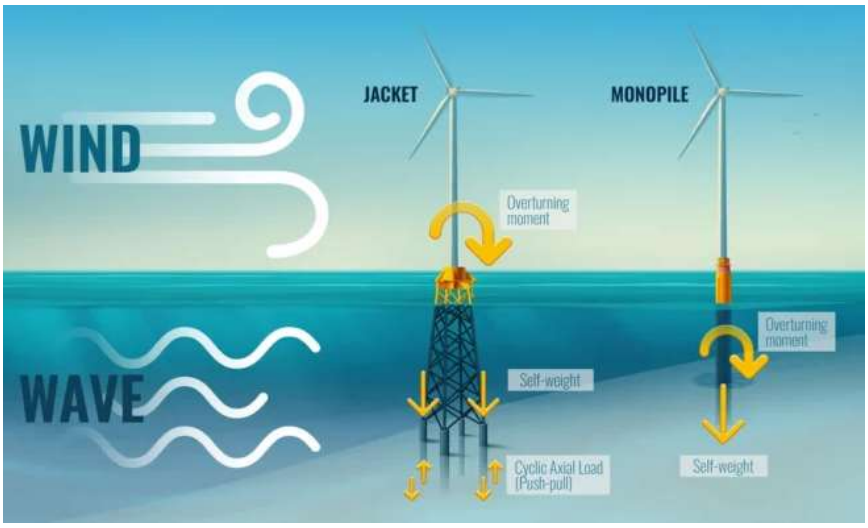
Kuşkusuz, hem yüksek doğruluk değerlerine sahip sonuçlar elde etmek için hassas analizler gerçekleştirme zorunluluğu dolayısıyla, hem de yapıların büyüklüğüyle ve karmaşıklığıyla orantılı olan büyük ağ yapısından dolayı bu tarz gerçekçi simülasyonların hem zaman bakımından hem de donanım bakımından maliyetleri oldukça yüksektir. Ayrıca bir parametre değişiminde simülasyonun en baştan tekrarlanması ihtiyacı da parametrik analizlerdeki maliyetlerin daha da artmasına sebebiyet vermektedir. Bu sebeple Reduced Order Modelling (ROM – düşük mertebeli modelleme) ve matematiksel tepki fonksiyonlarının kullanılması, simülasyon süreçlerinin doğruluktan ödün verilmeden kısaltılması ve kolaylaştırılması bakımından önem taşır.

ROM, hesaplamalı akışkanlar dinamiği ve yapısal analiz gibi yüksek hesaplama maliyetine sahip sayısal analizlerin sonuçlarını, daha düşük boyutlu matematiksel bir modelle temsil etmeyi amaçlayan indirgeme tekniğidir. Bu yöntem, tam mertebeli modellerin (Full Order Model – FOM) davranışını tanımlayan binlerce denklemi veya serbestlik derecesini, sistemin dinamik özelliklerini koruyarak daha az sayıda bağımsız bileşenle ifade eder (Benner vd., 2015). ROM'un temel amacı, karmaşık sistemlerin hesaplanma süresini büyük ölçüde azaltırken fiziksel doğruluğunu korumaktır. Bunun için genellikle Proper Orthogonal Decomposition (POD) gibi yöntemlerle sistemin baskın enerji modları belirlenir ve bu modlar üzerinden indirgenmiş bir temsili model oluşturulur. Böylece, örneğin bir yüzer rüzgâr türbininin akışkan–katı etkileşimi gibi çoklu fizik analizlerinde günler süren hesaplamalar saniyeler içinde sonuçlanabilir.

Yüzer temelli türbinler için ROM, farklı çevresel koşullarda sistem tepkisinin (yer değiştirme, eğilme momenti, güç üretimi vb.) hızlı biçimde tahmin edilmesine olanak tanır. Bu özellik, bilhassa tasarım optimizasyonu ve fizibilite çalışmaları sırasında maliyetleri düşürmek ve tasarım süresini kısaltmak açısından stratejik öneme sahiptir.

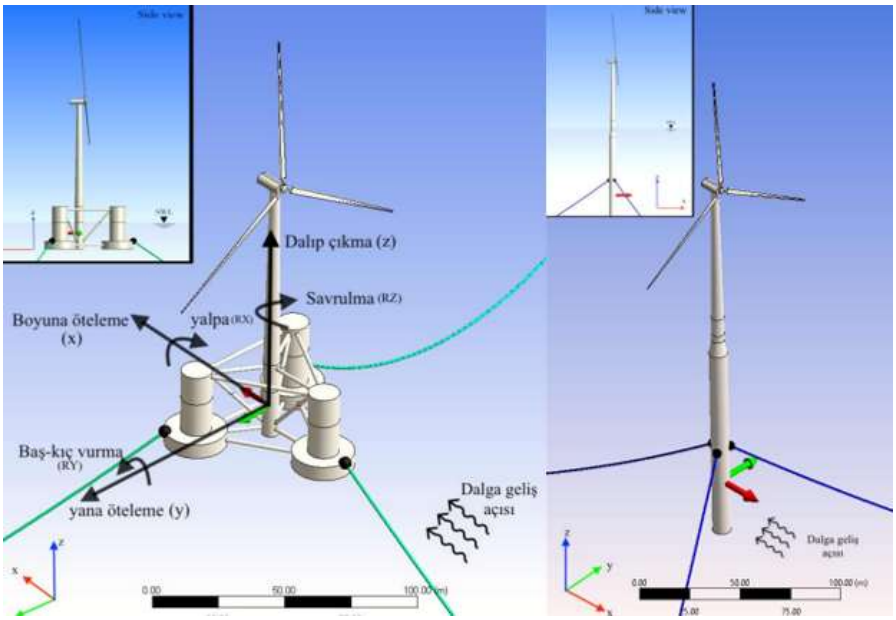
Simülasyonların Kapsamı ve Örnekleri

Sabit tabanlı türbinlerde rijitlik yüksek olduğu için serbestlik derecesi düşüktür ve yapılar çoğunlukla eğilme momentleri altında çalışır (Şekil 8 ve 9). Bu durumda, yorulma ve plastik deformasyonun doğru modellenmesi, ömür tahmini açısından kritik önemdedir (Yeter ve Garbatov, 2014).



Şekil 9: Farklı sabit temel tiplerine sahip deniz üstü rüzgâr türbinlerine etkiyen yükler ve türbin tepkisi (Bentley Blog, 2022)

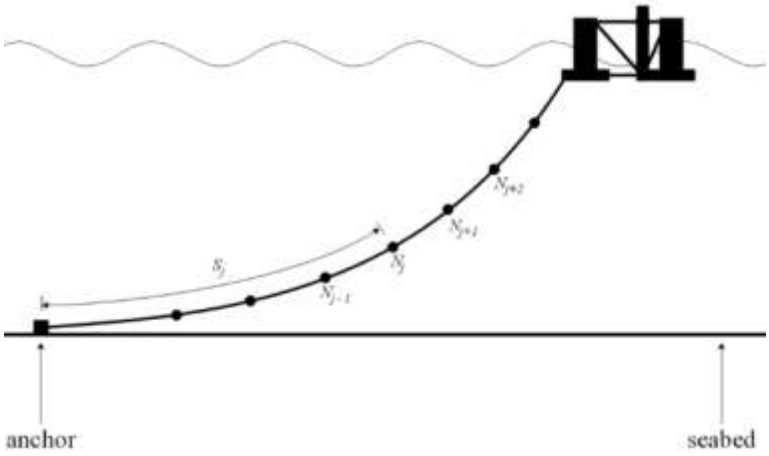
Yüzer türbinler, altı serbestlik derecesine sahip hareket dinamiği açısından karmaşık sistemlerdir. Bu tür platformlar genellikle çelik halatlarla (catenary mooring lines) deniz tabanına sabitlenir (Şekil 8 ve 9). Aktaş vd. (2018), yarı batık (semi-submersible) tipi temeli ve spar tipi temeli karşılaştırarak sayısal modellerin doğruluğunu değerlendirmiştir (Şekil 10). Çalışmada kaldırma kuvveti, balast sistemi ve doğal frekans analizleri incelenmiş; elde edilen sonuçlar deneysel veriler ve OC3/OC4 doğrulama modelleriyle karşılaştırılmıştır. Bu yaklaşım, simülasyon yazılımlarının gerçek sistem davranışını temsil etme yetkinliğini test etmiştir.



Şekil 10: Farklı yüzer temel tiplerinin sayısal modellenmesi- Yarı Batık tipi (semi-submersible, solda), Spar tipi (sağda) (Aktaş vd., 2018)

Yüzer türbinlerin demirleme sistemleri, platform dinamiğinde belirleyici unsurlardan biridir. Alkarem vd. (2021) çalışmalarında zincirleme hattı modelleriyle, kabloların kütlesi, akış sürüklemesi, elastik deformasyon ve eğilme momentlerinin sistem üzerindeki etkilerini

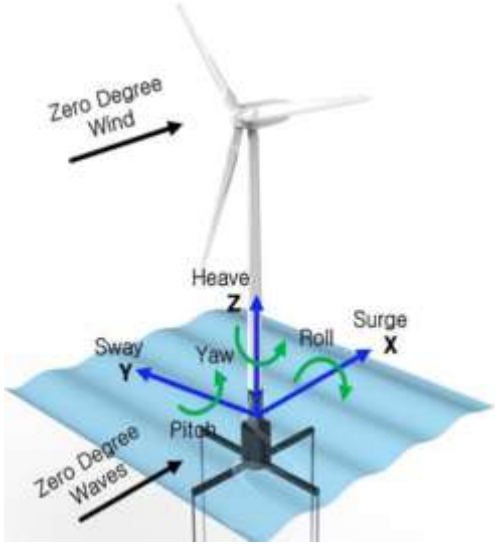
incelemiştir. Ayrıca ani gerilme (snap load) durumları analiz edilerek kablo güvenliği değerlendirilmiştir (Şekil 11).



Şekil 11: Demirlemenin modellenmesi (Alkarem vd., 2021)

Yüzer türbin simülasyonlarında dinamik davranışı doğru tanımlayabilmek için hem sınır koşullarının hem de çözüm algoritmalarının doğru belirlenmesi gereklidir. Tran vd. (2015) tarafından önerilen UBEM (Unsteady Blade Element Momentum) yöntemi, üç boyutlu akış modellemesinin yüksek hesaplama maliyetini azaltmak için geliştirilmiş bir yaklaşımdır (Şekil 12). Bu yöntem, kanat elemanlarına etki eden kuvvetleri bir boyutlu momentum denklemleriyle hesaplayarak, yüksek doğrulukta ancak düşük maliyetli aerodinamik sonuçlar elde edilmesini sağlar.

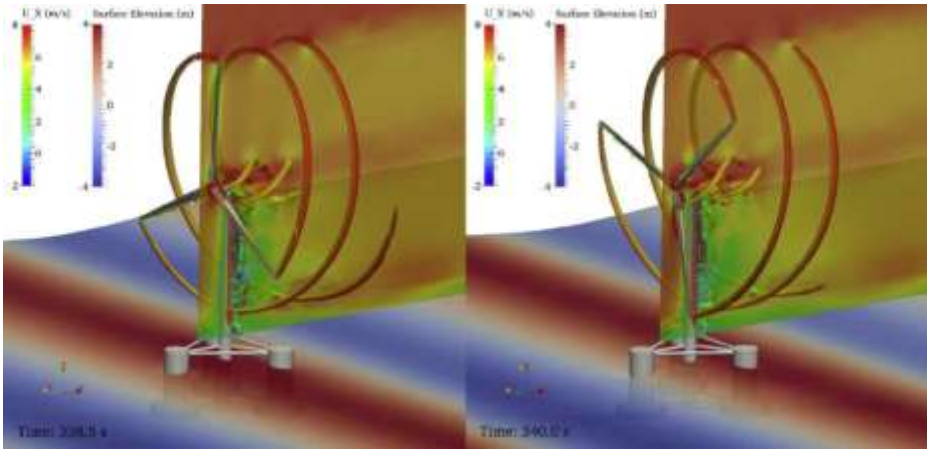
Zhang vd. (2020) çalışmasında, türbinin dalga etkisi altındaki hareketlerini analiz etmek için frekans alanı ve zaman alanı denklemleri tanımlanmıştır. Bu modellerde sistemin atalet momenti, radyasyon sönümü, viskoz etkiler ve dalga kuvvetleri dikkate alınmıştır. Elde edilen sonuçlarla, türbinin çevresel yükler altındaki yer değiştirme, hız ve ivme tepkileri belirlenmiş ve zaman-bağımlı güç üretimi tahmin edilmiştir.



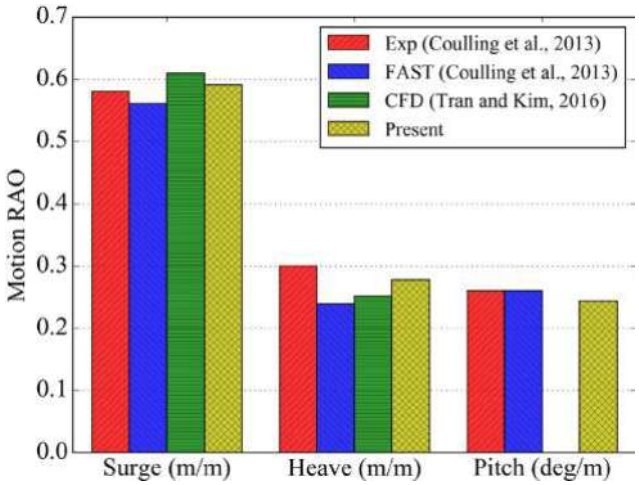
Şekil 12: Deniz üstü yüzer temelli rüzgâr türbininin altı serbestlik derecesi (Tran vd., 2015)

Liu vd., (2017) gerçekleştirdiği çalışmada, yüzer rüzgâr türbinlerinin aerodinamik ve hidrodinamik davranışlarını aynı anda temsil edebilmek için tam akuple HAD analizleri (fully coupled simulations) uygulanmıştır (Şekil 13). Analizlerde, rüzgâr–dalga–yapı etkileşimlerini

birlikte ele alan FSI (Fluid–Structure Interaction) yaklaşımı kullanılmıştır. Bu yöntemin tercih edilmesinin nedeni, yüzer platformun altı serbestlik derecesine sahip karmaşık dinamik davranışlarının ve kanat dönme momentlerinin, çevresel yüklerle etkileşimini doğru biçimde saptayabilmesidir (Şekil 14). Elde edilen sonuçlar, özellikle platform hareketleri, rotor momentleri ve kuplajlı akış alanlarının zamanla değişimini ortaya koymuştur. Ancak çalışma, bu analizlerin yüksek çözüm ağına, zamana bağlı çözüm yöntemlerine ve türbinin her bir zaman adımında yapı deformasyonlarının güncellenmesine ihtiyaç duyduğunu göstermektedir. Bu durum, hesaplama süresini günler mertebesine çıkararak yüksek donanım gereksinimi doğurmaktadır. Dolayısıyla bu tür tam akuple analizler, doğruluk açısından kritik olsa da mühendislik uygulamalarında hızlı karar verme süreçlerinde pratik değildir. Bu bağlamda, literatürde elde edilen bu yüksek doğruluk derecesine sahip sonuçlar, Reduced Order Model (ROM) oluşturulması için temel veri kaynağı niteliğindedir. ROM yaklaşımı, bu tip karmaşık FSI analizlerinden elde edilen verileri kullanarak saniyeler içinde tepki fonksiyonlarını tahmin edebilme potansiyeliyle, tasarım süreçlerini büyük ölçüde hızlandırabilir.



Şekil 13: Yarı-batık temelli deniz üstü rüzgar türbini akuple simülasyonu (Liu vd., 2017)



Şekil 14: Savrulma, batma-çıkma ve eğilme tepkileri için RAO karşılaştırması. (Liu vd., 2017)

OC5 Projesi'nin ikinci aşamasında, DeepCwind yarı batık yüzer rüzgâr türbini sistemi hem 1/50 ölçekli havuz testleri hem de sayısal modeller aracılığıyla analiz edilmiştir (Robertson vd., 2017). Çalışmanın amacı, yüzer rüzgâr türbinlerinin toplam yüklerinin (global loads)

doğrulanması ve farklı modelleme yaklaşımlarının sonuçlar üzerindeki etkilerinin değerlendirilmesidir (Şekil 15). Bu kapsamda, çeşitli kurumlar tarafından geliştirilen aerodinamik, hidrodinamik ve halat bağlama modelleri karşılaştırılmış; özellikle dinamik halat modelleri, nonlineer dalga kinematiği ve süreksiz aerodinamik modellerin doğruluğu artırdığı belirlenmiştir. Doğrulama, MARIN test havuzunda gerçekleştirilen deneylerden elde edilen ölçümlerle yapılmış; sekiz farklı rüzgâr–dalga senaryosu için nihai (ultimate) ve yorulma yükleri simülasyonlarla karşılaştırılmıştır (Şekil 16). Elde edilen sonuçlar, genel yük tahminlerinde yüksek tutarlılık göstermiş ancak kule tepe momentlerinde ve ön halat gerilmelerinde lineer dalga bölgesinin ötesindeki dalga uyarımlarının eksik temsil edilmesinden kaynaklı sapmalar gözlenmiştir. Bu çalışma, FSI temelli modellerin doğrulanması açısından literatürdeki en kapsamlı örneklerden biridir ve yüksek doğrulukla elde edilen bu sonuçlar, gelecekte ROM oluşturma süreçleri için kritik bir referans veri tabanı sağlamaktadır. Böylece, günler süren FSI simülasyonları yerine, bu verilerle eğitilmiş ROM modelleri kullanılarak sistem tepkileri saniyeler içinde tahmin edilebilir.

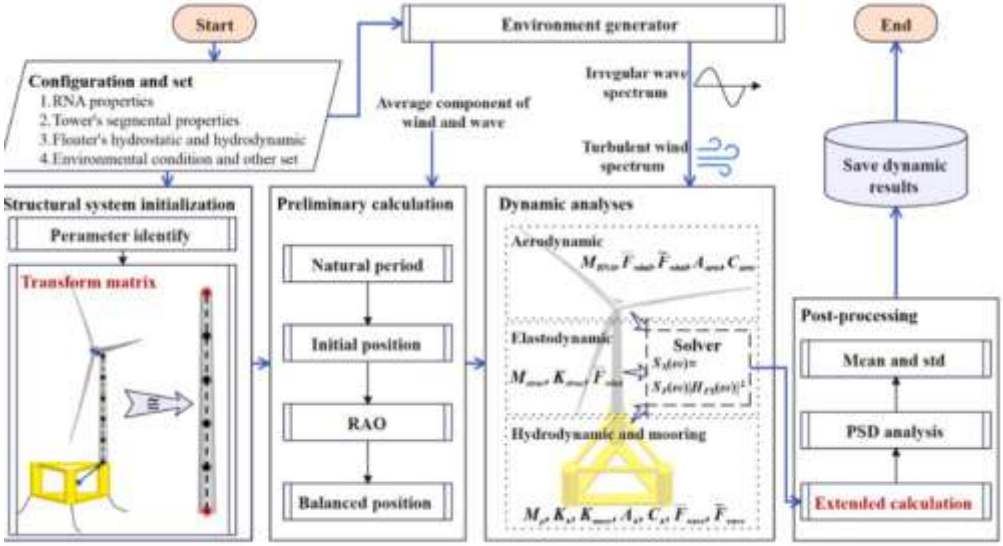
Li vd., (2025a) çalışmalarında, yüzer rüzgâr türbini platformlarının kavramsal tasarım sürecini hızlandırmak ve maliyetleri azaltmak için bir Entegre Tasarım Optimizasyon (IDO) çerçevesi geliştirmişlerdir. Tasarım sürecinde üç ana modül kullanılmıştır: Floater tasarımı, entegre modelleme ve analiz, ayrıca optimizasyon. İlk modül, panel ağ oluşturma, adaptif balast dağılımı, hidrostatik özellik analizi ve hidrodinamik katsayıların hesaplanmasını içerirken; ikinci modül frekans-domain (FD) kodu ile platformun dinamik tepkilerinin hızlı şekilde tahmin edilmesini sağlamıştır (Şekil 17). Üçüncü modül ise stabilite, güvenlik ve maliyet-etkinlik kriterlerine göre tasarım boyutlarını optimize etmiştir. Çalışma, 15 MW sınıfı bir türbin için üç sütunlu yarı-batık (semi-submersible) bir platform üzerinde bir “case-study” uygulaması sunmaktadır ve bu yöntemle baş-kıç vurma (pitch) hareketlerinde %40 düşüş, kule tabanındaki baş-kıç eğilme momentinde ise %17 azalma sağlandığını göstermektedir. Bu yaklaşım, geleneksel çok-serbestlik dereceli FSI (akuple aero-hidro-yapı) simülasyonlarına kıyasla önemli ölçüde daha düşük donanım ve zaman gereksinimi sunmakta; bu durum, ilerleyen çalışmalarda ele alacağınız ROM yaklaşımının gerekçesiyle doğrudan örtüşmektedir.

Participant	Code	Aerodyn.		Hydrodynamics							Moorings		
		Dyn. Wake	Unst. Airfoil	2nd + WK	1st PF	2nd PF	ME	Meas. Wave	Stretch	Inst. Pos.	Dyn.	Hydro Exc.	Seabed Fric.
4Subsea	OrcaFlex-FAST v8												
CENER	FAST v6 + OPASS												
CENTEC	FAST v8												
DNV GL	Bladed 4.8												
DTU ME	HAWC2												
DTU PF	HAWC2												
ECN-MARIN	aNySIM-PHATAS v10					Diff.-only							
IFE	3DFloat												
IFP_PRI	DeepLines Wind V5R2												
NREL PF	FAST v8												
NREL ME	FAST v8												
POLIMI	FAST v8.15			Diff.-only									
Siemens PLM	Samcef Wind Turbines												
Tecnalia F7O	FAST v7 + OrcaFlex 9.7												
Tecnalia F8	FAST v8.16												
UC-IHC	Sesam												
UOU	UOU + FAST v8												
UPC	UPC + FAST												
UTokyo	NK-UTWind												
WavEC FAST	FAST v8												
WavEC FF2W	FF2W												

Şekil 15: Doğrulama çalışmasında yer alan katılımcıların, kullanılan araçların/kodların ve modelleme yaklaşımının özeti. (Robertson vd., 2017)

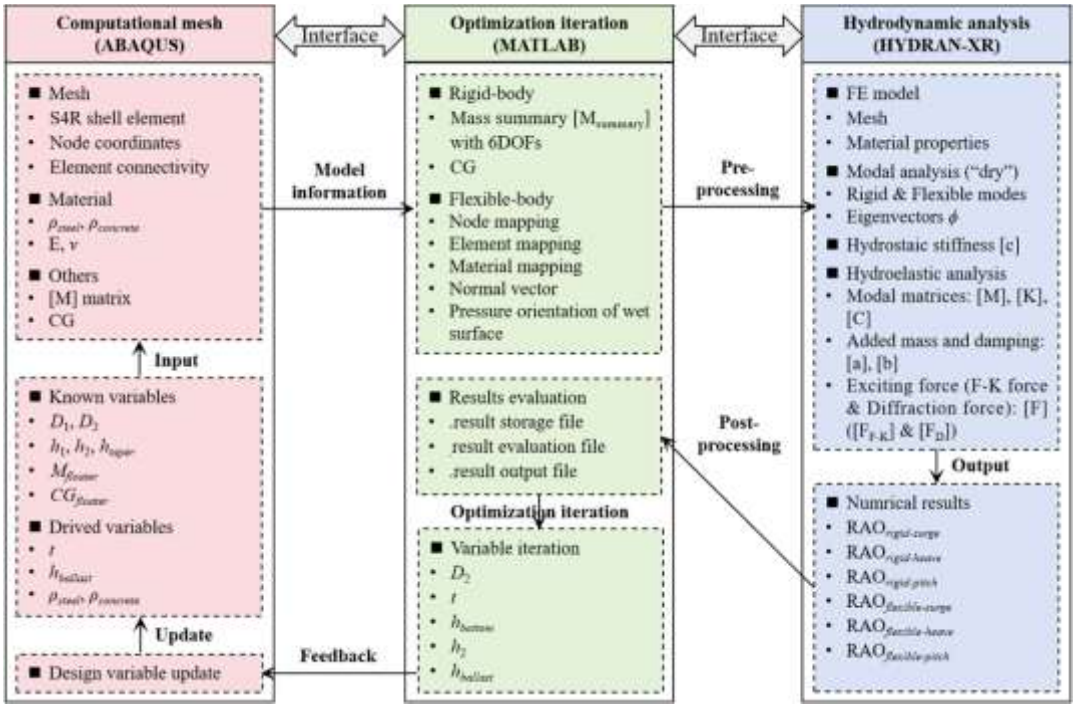
Load Case	Description	rpm	Blade Pitch (deg)	Wave Condition	Wind Condition	Sim. Length (min)
3.3	Operational Wave	0	90	Irregular: H_s = 7.1 m, T_p = 12.1 s, γ=2.2, JONSWAP	N/A	176
3.4	Design Wave	0	90	Irregular: H_s = 10.5 m, T_p = 14.3 s, γ=3.0, JONSWAP	N/A	180
3.5	White Noise Wave	0	90	White noise: H_s = 10.5 m, T_{range} =6-26 s	N/A	180
4.1	Oper. Wave Steady Wind 1	12.1	1.2	Irregular: H_s = 7.1 m, T_p = 12.1 s, γ=2.2, JONSWAP	$V_{hub,x}$= 12.91 , $V_{hub,z}$= -0.343 σ_x = 0.5456, σ_z = 0.2376	180
4.2	Oper. Wave Steady Wind 2	12.1	15.0	Irregular: H_s = 7.1 m, T_p = 12.1 s, γ=2.2, JONSWAP	$V_{hub,x}$ = 21.19, $V_{hub,z}$ = -0.600 σ_x = 0.9630, σ_z = 0.4327	180
4.3	Oper. Wave Dynamic Wind	12.1	1.2	Irregular: H_s = 7.1 m, T_p = 12.1 s, γ=2.2, JONSWAP	NPD spectrum, μ = 13.05	180
4.4	Design Wave Steady Wind 1	12.1	1.2	Irregular: H_s = 10.5 m, T_p = 14.3 s, γ=3.0, JONSWAP	$V_{hub,x}$= 12.91 , $V_{hub,z}$= -0.343 σ_x = 0.5456, σ_z = 0.2376	180
4.5	White N. Wave Steady Wind 1	12.1	1.2	White noise: H_s = 10.5 m, T_{range} = 6-26 s	$V_{hub,x}$= 12.91 , $V_{hub,z}$= -0.343 σ_x = 0.5456, σ_z = 0.2376	180

Şekil 16: Doğrulama testi (yük) durumlarının açıklaması (Robertson vd., 2017)



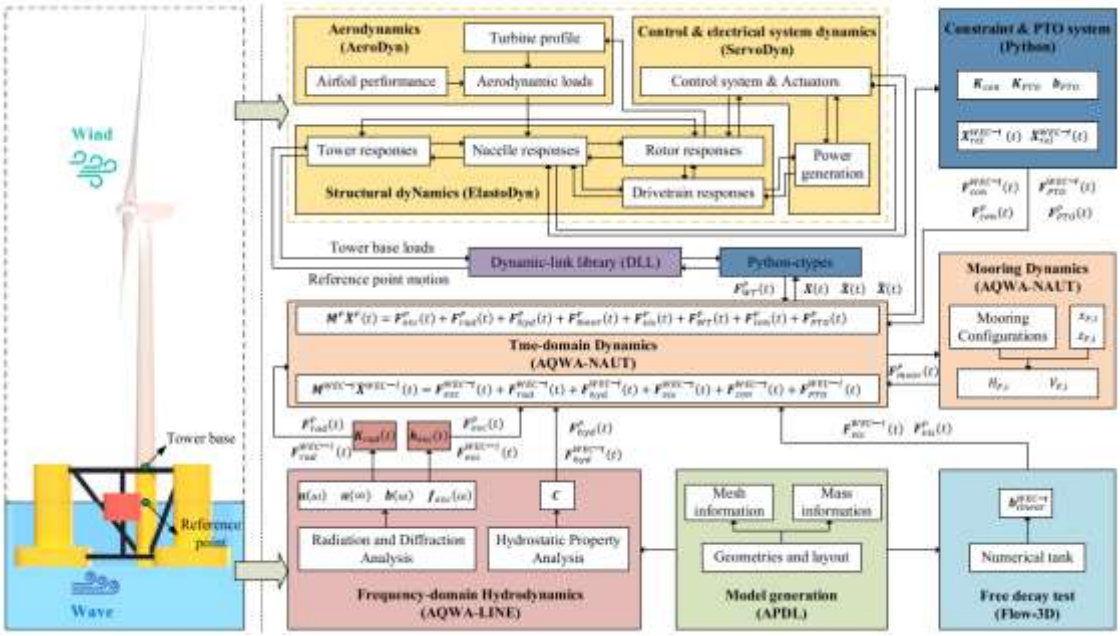
Şekil 17: Frekans düzlemli hesaplama akış şeması (Li vd., 2025a)

Ma vd., (2025) çalışmalarında, OC3-spar tipi yüzer rüzgâr türbininin rijit hareket ve hidroelastik tepkisine dayalı olarak kapsamlı bir tasarım optimizasyonu yapmışlardır. Çalışmada kullanılan yöntem, HYDRAN-XR yazılımı ile ABAQUS–MATLAB entegrasyonuna dayanmakta olup; dalga yükleri altında rijit ve esnek gövde davranışlarını eşzamanlı değerlendiren bir çok-amaçlı pareto-ön cephesi algoritması uygulanmıştır. Optimizasyon değişkenleri arasında alt silindirik kısmın çapı, cidar kalınlığı, su çekimi derinliği ve balast yüksekliği yer almış; amaç fonksiyonu ise yapının boyuna ötelenme (surge), dalıp-çıkma ve baş-kıç vurma yönlerindeki tepki genlik operatörlerinin (RAO) minimize edilmesi olarak belirlenmiştir. Hidroelastik analizde potansiyel akış teorisi ile sınır elemanlar yöntemi birleştirilmiş, deformasyonlar sonlu eleman modal üst üste bindirme tekniğiyle elde edilmiştir (Şekil 18). Optimizasyon sonucunda spar platformun $\gamma = 5{,}41$ incelik oranı ve CG = –54 m konfigürasyonu ile boyuna ötelenme, dalıp-çıkma ve baş-kıç vurma hareketlerinde %20–40 oranında azalma sağlanmıştır. Çalışma, rijit modellemenin mühendislik düzeyinde kabul edilebilir olduğunu, ancak gerilme ve yorulma analizlerinde hidroelastik etkilerin göz ardı edilmemesi gerektiğini vurgulamaktadır. Bu kapsamlı optimizasyon süreci günler süren analiz gerektirmiştir ve literatürdeki yüksek doğruluk derecesine sahip bu veriler, Reduced Order Model tabanlı hızlı tepki fonksiyonu oluşturma yaklaşımları için kritik bir eğitim veri kümesi niteliği taşımaktadır.



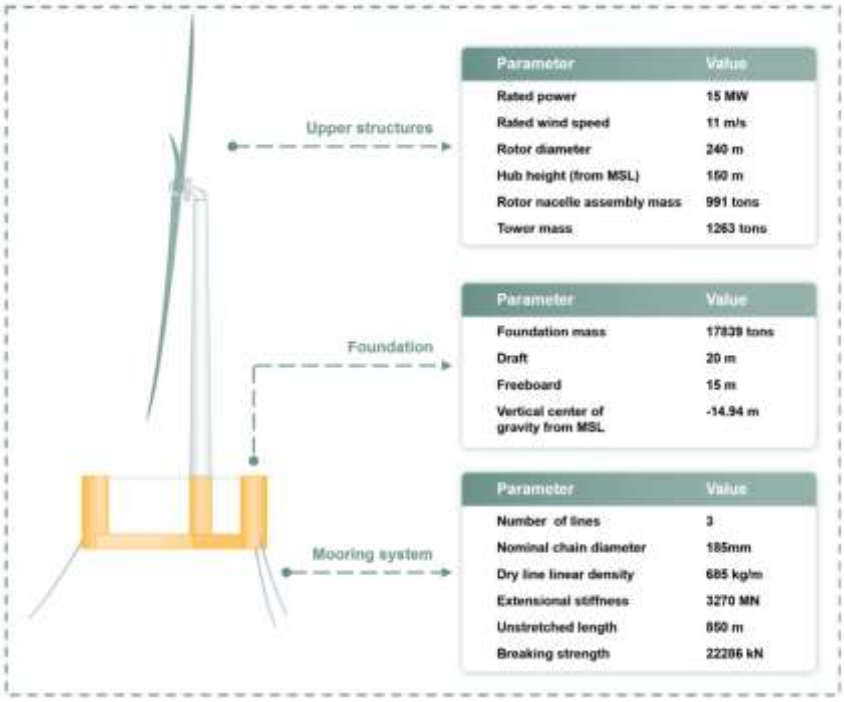
Şekil 18: Optimizasyon akış şeması (Ma vd., 2025)

Han vd. (2024), dalga ve rüzgâr enerjisini birlikte kullanan yüzer hibrit sistemlerin karmaşık dinamik davranışlarını çözümlemek amacıyla OFPA (OpenFAST-AQWA Python Architecture) adını verdikleri tam akuple aero-hidro-servo-elastik-mooring-multibody sayısal simülasyon çerçevesini geliştirmişlerdir (Şekil 19). Bu iş akışı, OpenFAST'in aerodinamik modüllerini ANSYS AQWA'nın hidrodinamik çözücüsüyle bütünleştirmiş, Python tabanlı harici kuvvet modülüyle PTO (Power-Take-Off) ve kılavuz-ray (guide-roller) sistemlerinin doğrusal olmayan etkileşimlerini modellemiştir. Geliştirilen model, 5 MW'lık OC4-DeepCwind tipi yarı batık platform ve heave tipi dalga enerjisi konverterlerin birleşiminden oluşan bir hibrit sistemde doğrulanmıştır. OFPA, farklı dalga-rüzgâr koşullarında sistemin altı serbestlik dereceli (6-DOF) hareketini, PTO sönüm etkilerini ve güç üretimini zamana bağlı olarak çözebilmiştir. Deneysel sonuçlarla yapılan karşılaştırmalar, OFPA'nın hem yüzer rüzgâr türbini hem de dalga enerjisi konverter bileşenlerinin hareket genliklerini yüksek doğrulukla tahmin ettiğini göstermiştir. Bununla birlikte, çalışmada bildirilen analizlerin her bir senaryosu için yüksek çözünürlüklü ağ yapısı ve paralel işlem desteği gerektiği, dolayısıyla birkaç gün süren hesaplama maliyetine sahip olduğu belirtilmiştir. Bu nedenle, bu tür tam akuple (FSI) simülasyonlardan elde edilen doğrulanmış veriler, ROM tabanlı yaklaşımların eğitimi ve doğrulanması açısından kritik öneme sahiptir; böylece benzer doğrulukta sonuçlar saniyeler içinde elde edilebilir.

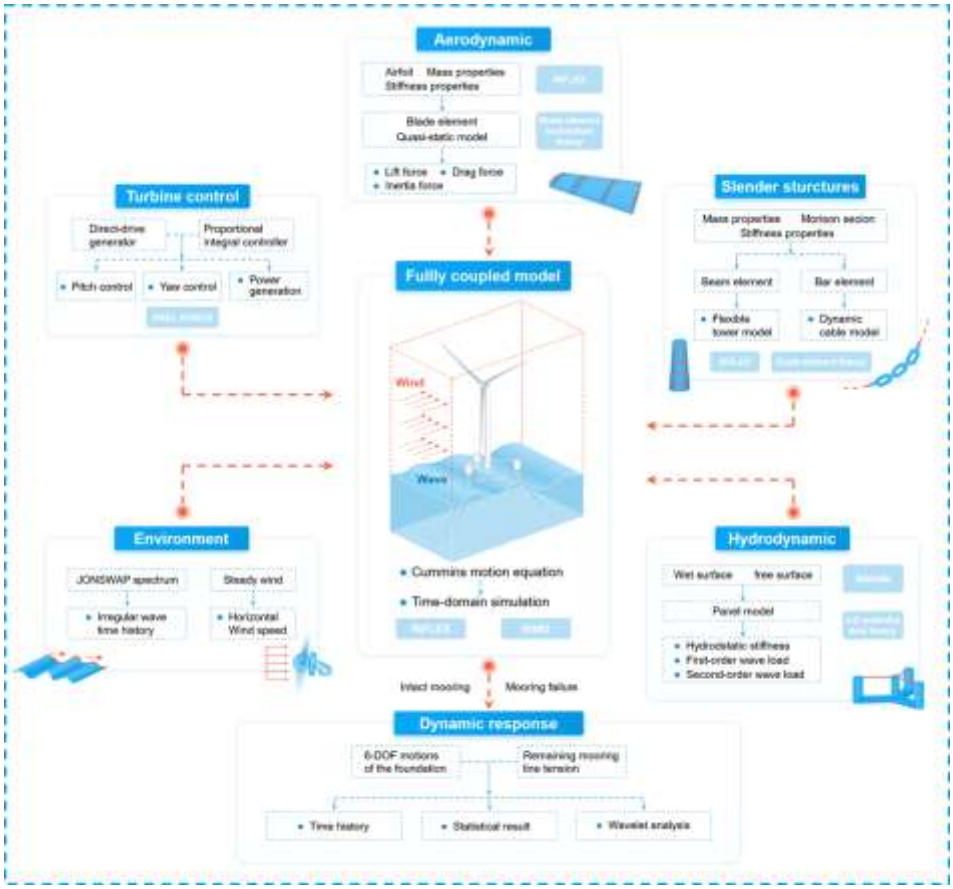


Şekil 19: Hibrit sistem dinamik analizi için tam akuple aero-hidro-servo-elastik-demirleme-çok gövdeli sayısal simülasyon şeması (Han vd., 2024)

Li vd. (2025a) ve Li vd. (2025b), 15 MW yarı-batık (semi-submersible) VolturnUS-S tipi yüzer rüzgâr türbininde (Şekil 20) bir halat kopması sonrası meydana gelen dinamik davranışları analiz etmek üzere tam akuple aero-hidro-servo-elastik bir model geliştirmiştir. Model, BEM (Blade Element Momentum) teorisine dayalı aerodinamik yükleri, potansiyel akış teorisi ve Boundary Element Method (BEM) tabanlı hidrodinamik kuvvetleri, ayrıca sonlu eleman yöntemi (FEM) yaklaşımıyla modellenmiş halat dinamiklerini içeren SIMO–RIFLEX yazılımı üzerine kurulmuştur (Şekil 21). Çalışmada dört senaryo (normal, halat kopması + kule ekseni çevresinde dönme hatası, halat kopması + acil durdurma, aktif kontrol) ele alınmış; her biri için 6 serbestlik dereceli (6-DOF) hareketler ve kalan halat gerilmeleri zaman-frekans (wavelet) analiziyle incelenmiştir. Sonuçlar, halat kopması sonrası platformda düşük frekanslı "slow drift" hareketlerinin geliştiğini ve boyuna öteleme yönünde 776 m'ye kadar sapma oluşabileceğini göstermektedir. Ayrıca, acil durdurma manevrasının sürüklenmeyi azaltmakla birlikte sistemin yeniden dengeye gelme süresini uzattığı ve halat gerilmelerinde yüksek frekanslı yorulma bileşenlerini artırdığı belirtilmiştir. Bu kapsamlı simülasyonlar, her senaryo için yaklaşık birkaç bin saniyelik zaman adımıyla günler süren hesaplama yükü oluşturmuştur. Dolayısıyla, bu tür yüksek doğruluklu FSI analizleri, ROM tabanlı yöntemlerin eğitilmesi ve doğrulanması için kritik referans veriler sağlamaktadır; ROM sayesinde benzer senaryoların tepkisi gelecekte saniyeler içinde tahmin edilebilir hale gelebilecektir.



Şekil 20: Deniz üstü yüzer temelli rüzgâr türbininin ve demirleme sisteminin özellikleri. (Li vd., 2025b)



Şekil 21: İş akışı görünümü (Li vd., 2025b)

SONUÇ

Yüzer rüzgâr türbinlerinin dinamik davranışlarının doğru biçimde modellenebilmesi, aerodinamik, hidrodinamik, yapısal ve kontrol sistemlerinin birbirleriyle olan etkileşimlerinin bütüncül olarak ele alınmasını gerektirir. Bu kapsamda kullanılan tam akuple analizler (FSI – Fluid–Structure Interaction), sistemin altı serbestlik derecesine sahip karmaşık hareketlerini, dalga ve rüzgâr kaynaklı zamana bağlı yük değişimlerini ve geri besleme etkilerini eş zamanlı olarak çözebilmektedir. Ancak, bu tür yüksek doğruluklu analizlerin en büyük dezavantajı, çözüm sürelerinin uzunluğu ve hesaplama maliyetlerinin yüksekliğidir.

Bir yüzer türbin modeli, aerodinamik (rüzgâr alanı ve kanat yükleri), hidrodinamik (dalga kuvvetleri, radyasyon ve difraksiyon etkileri), yapısal (gövde ve kule deformasyonları) ve kontrol sistemleri (pitch–yaw kontrolleri, PTO sistemleri) olmak üzere dört ana bileşenin karşılıklı etkileşimini içerir. Bu bileşenlerin her biri için zamana bağlı denklemlerin eşzamanlı çözülmesi gerekir. Dolayısıyla çözüm süresi, modelin ağ yoğunluğu ve zamansal çözünürlüğü ile doğru orantılı olarak artar. Özellikle dalga spektrumlarının ve akış alanlarının üç boyutlu olarak modellenmesi, çözümün haftalarca sürebildiği durumlara yol açabilir.

Yüksek çözünürlüklü HAD veya FSI tabanlı bu analizlerin hesaplama maliyetleri, erken tasarım aşamalarında optimum türbin konfigürasyonlarının belirlenmesini zorlaştırır. Her senaryo için yüzlerce simülasyon yapılması gerektiğinde, sürecin toplam hesaplama yükü binlerce CPU-saat düzeyine ulaşabilir. Bu nedenle mühendislik uygulamalarında, tam akuple modellerin yalnızca doğrulama veya nihai tasarım aşamalarında kullanılması yaygın bir yaklaşımdır.

Bu noktada Reduced Order Model (ROM) yaklaşımları devreye girmektedir. ROM, yüksek çözünürlüklü sayısal modellerden veya deneysel verilerden elde edilen fiziksel ilişkileri indirgenmiş bir matematiksel yapı hâline getirerek, aynı sistem tepkilerini çok daha kısa sürede belirlemeyi amaçlar. Böylece, tam akuple bir analizin günler süren hesaplaması yerine, benzer doğrulukta sonuçlar saniyeler içinde elde edilebilir. ROM'un en büyük avantajı, yüksek doğruluk ile düşük hesaplama maliyetini birleştirmesidir. Bu sayede mühendislik süreçlerinde hızlı optimizasyon, çoklu senaryo analizi ve kontrol stratejilerinin gerçek zamanlı testleri mümkün hâle gelir.

Sonuç olarak, deniz üstü yüzer rüzgâr türbinlerinde tam akuple analizlerin fiziksel doğruluk açısından vazgeçilmez olduğu, ancak tasarım döngüsünde kullanılabilirliğini sınırlayan temel faktörün hesaplama maliyeti olduğu görülmektedir. Bu nedenle, tam akuple analizlerden elde edilen güvenilir verilerin indirgenmiş matematiksel modeller yani ROM aracılığıyla yeniden yapılandırılması, modern rüzgâr enerjisi mühendisliğinde hem hız hem de doğruluk dengesini sağlayan yeni bir paradigma olarak öne çıkmaktadır.

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YÜKSEK SÜRATLİ KAYICI TEKNE FORMLARININ KADEME (STEP) TASARIMI AÇISINDAN ANALİZİ

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ÖZET

Yüksek süratli tekneler, yüksek hız ve manevra kabiliyetleri ile performans gereksinimlerini karşılamak amacıyla tasarlanarak üretilen teknelerdir. Bu nedenlerle seyir halinde, tekne gövdesinin hidrodinamik direncinin mümkün olduğu kadar az olması beklenir. Ancak, yüksek süratli tekneler, yalnızca yarış amacıyla tasarlanıp üretilmezler; günümüzde çoğunlukla eğlence amaçlı tekneler, devriye ve ambulans tekneleri de bu kapsamda üretilmektedirler. Bu çalışma, kademeli ve kademesiz gövdeli teknelerin hidrodinamik incelemesini ele alarak, kademeli gövde tasarımı ile ilişkili performans avantajlarını ve dezavantajlarını değerlendirmeyi amaçlamaktadır. Bu amaç doğrultusunda öncelikle modeller beş farklı gövde tipinde oluşturulmuştur. Bunlar arasından kayma rejimi için en uygun tekne modeli olan "çeneli derin V karinalı tekne" modeli seçilmiş, tekne, L=14 m boyunda kademeli ve kademesiz gövde formunda tasarlanarak ayrıntılı olarak incelenmiştir. Hesaplamalı akışkanlar dinamiği (HAD) simülasyonları kullanılarak yapılan çalışmada, viskoz ve dalga direncinin azaltılması, kaldırma kuvveti üretimi, kayma rejiminin verimliliği ve değişen çalışma koşulları altında stabilite gibi temel parametreler analiz edilmiştir. Bulgular, kademeli gövde konfigürasyonlarının ıslak yüzey alanını önemli ölçüde azalttığı ve bunun sonucunda hidrodinamik direncin azaldığı ve daha yüksek hızlarda kaldırma kuvvetinin arttığı yönündedir. Bununla birlikte, çalışma aynı zamanda bu avantajların, özellikle dönüş manevralarında, yetersiz dinamik stabilite ile tekne kontrol zorluklarını da birlikte getirebileceğini göstermektedir.

Anahtar Kelimeler: Yüksek süratli tekneler; Kademeli gövdeli kayıcı tekneler; Hidrodinamik direnç; HAD.

ANALYSIS OF HIGH-SPEED PLANING BOAT FORMS IN TERMS OF STEP DESIGN

ABSTRACT

High-speed boats are specifically designed to meet performance standards for speed and maneuverability. As a result, the hull is intended to minimize hydrodynamic resistance during cruising. However, high-speed boats are not only built for racing; today, they are mainly used as recreational, patrol, and ambulance vessels. This study aims to evaluate the performance benefits and drawbacks of stepped hull designs by examining the hydrodynamics of stepped and non-stepped hulls. For this purpose, models were initially created for five different hull types. Among these, the most suitable boat model for the planing regime was selected as the "Hard Chine Deep V" model, and the boat was designed with both stepped and non-stepped hull forms, each with a length of L=14 m, and examined in detail. Using computational fluid dynamics (CFD) simulations, the study analyzed key parameters such as the reduction of viscous and wave resistance, lift generation, planning efficiency, and stability under various operating conditions. The findings indicate that stepped hull configurations substantially decrease wetted surface area, leading to lower hydrodynamic drag and increased lift at higher speeds. However, the study also points out that these advantages can be offset by insufficient dynamic stability and hull control challenges, especially during turning maneuvers.

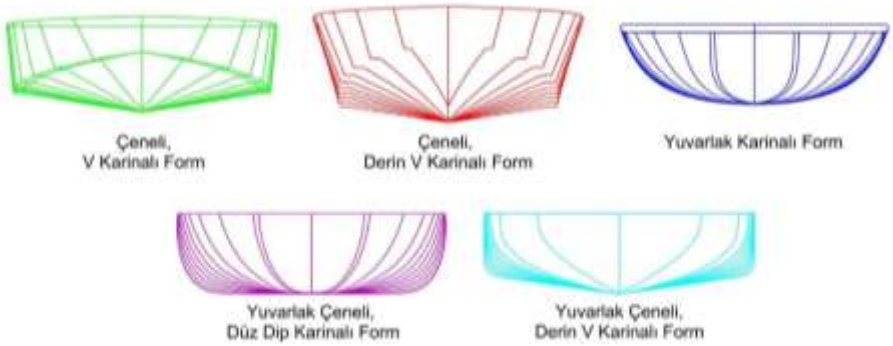
Keywords: High-speed boats; Stepped hull planing hulls; Hydrodynamic resistance; CFD.

GİRİŞ

Yüksek süratli tekneler, yüksek hız ve manevra kabiliyeti ile performans gereksinimlerini karşılamak amacıyla tasarlanarak üretilen teknelerdir. Bu nedenlerle tekne gövdesinin seyir halindeki hidrodinamik direncinin mümkün olduğu kadar düşük olması beklenir. Yüksek süratli tekneler, yalnızca yarış amacıyla tasarlanıp üretilmezler; günümüzde çoğunlukla eğlence amaçlı tekneler, devriye ve ambulans tekneleri de bu kapsamda üretilmektedirler

Yüksek hızlı teknelerde step (kademe), temel olarak hidrodinamik performansı ve stabiliteyi iyileştirmek amacıyla tekne gövdesine eklenen stratejik bir kesinti veya basamaktır. Bu tasarımın en kritik işlevi, teknenin altından geçen su akışını kontrollü bir şekilde ayırarak, gövdenin ıslak yüzey alanını ve dolayısıyla sürtünme (viskoz) direncini önemli ölçüde azaltmaktır. Step aynı zamanda, teknenin hızlandıkça doğal olarak yükselmesini (trim) kolaylaştırarak, daha verimli bir kayma rejimine daha çabuk geçiş sağlar. Bu sayede aynı motor gücüyle daha yüksek süratlere ulaşılabilir veya aynı hız için daha az güç ve yakıt tüketilir. Ek olarak, step, hava cebi oluşturarak su ile gövde arasına hava karışımını teşvik eder ve bu da direnci daha da düşürür. Sonuç olarak, step tasarımı, yüksek hızlı teknelerde hız, verimlilik, yakıt ekonomisi ve deniz tutuşu arasında optimal bir denge kurmak için vazgeçilmez bir mühendislik çözümüdür.

Bu çalışma, kademeli (stepli) ve kademesiz gövde konfigürasyonlarının hidrodinamik karakteristiklerini karşılaştırmalı bir yaklaşımla ele alarak, step geometrisinin performans üzerindeki etkilerini avantajları ve sınırlılıklarıyla birlikte ortaya koymayı hedeflemiştir. Araştırmanın başlangıç aşamasında, kayma (planing) rejiminde yüksek performans sunduğu değerlendirilen "çeneli derin V" karina formu, beş farklı gövde alternatifi arasından tercih edilmiş; bu form esas alınarak 14 m boyunda, biri kademeli diğeri kademesiz olmak üzere iki ayrı model oluşturulmuş ve söz konusu modeller ayrıntılı HAD (Hesaplamalı Akışkanlar Dinamiği) analizlerine tabi tutulmuştur.



Şekil 1: Çalışma kapsamında geliştirilen yüksek süratli teknelerin enkesitleri

1.STEP TASARIMI

1.1 Step Tasarımının Önemi, Amacı ve Çalışma Prensibi

Step tasarımının başarısı, yalnızca varlığına değil, aynı zamanda üç temel parametrenin titizlikle optimize edilmesine bağlıdır: açısı, yüksekliği ve tekne boyunca konumu. Step açısı, genellikle tekne taban çizgisine hafif açılı ayarlanır; suyun temiz bir şekilde ayrılmasını sağlamalı, ancak aşırı olmamalıdır. Çok dik bir açı suyu keser ancak türbülans ve dengesizliğe yol açabilir ken, çok sığ bir açı etkisiz kalabilir. Step yüksekliği ise gövde ile su arasında oluşacak hava cebinin boyutunu ve etkinliğini doğrudan belirler. Yetersiz yükseklik istenen direnç azalmasını sağlamaz, aşırı yükseklik ise teknenin dengesini bozabilir ve inişlerde (örn.

dalga üstünde seyir) yapısal strese neden olabilir. En kritik parametrelerden biri olan step konumu, teknenin ağırlık merkezi ve hidrodinamik kaldırma merkezi ile uyum içinde belirlenmelidir. Teknenin doğal trim açısını ve kalkış (planing) anında ki davranışını doğrudan etkiler. Çok geride olması burnun aşırı yükselmesine (bow-up), çok önde olması ise teknenin düz ve verimsiz bir şekilde seyretmesine neden olabilir. Bu üç parametrenin birbiriyle senkronize şekilde ayarlanması, maksimum performans, yakıt verimliliği ve güvenli seyir için hayati önem taşır.

1.2 Step Tasarım Parametreleri

Step açısının seçimi, teknenin öncelikli performans hedefine göre belirlenir: 1-2° dengeli hız ve verimlilik, 0.5-1.5° üstün stabilite, 2-3° erken kalkış, 3-5° ise maksimum hız için tercih edilir. Step yüksekliği ise tekne boyutu ve performans beklentisiyle doğrudan ilişkilidir. 10 mm'den az bir yükseklik küçük teknelerde minimal etki sağlarken, 10-25 mm aralığı 6-12 metrelik teknelerde genel kullanım için optimum dur. 25-50 mm gibi daha yüksek değerler ise yüksek performans ve yarış teknelerinde maksimum hava cebi oluşumu ve direnç azaltılması için kullanılır.

En kritik parametrelerden biri olan step konumu, genellikle teknenin pruvasından (burun ucundan) itibaren tekne boyunun (L) belirli bir yüzdesi olarak ifade edilir. Planing teknesi hidrodinamiği nin temel prensiplerine (Savitsky, 1964; Fridsma, 1969) göre, stepin ağırlık merkezinin (CG) gerisinde yer alması esastır. Endüstriyel uygulamada ve tasarım kılavuzlarında, optimum konum için pruvadan itibaren yaklaşık %55 ile %65 L aralığı yaygın bir kabul görmüştür. Bu aralık, teknenin kalkış (planing) anında istenen trim açısına ulaşmasını ve gövdenin arka kısmının verimli bir şekilde kaldırma kuvveti üretmesini sağlar. Konumun bu aralığın önüne kaydırılması, teknenin düz ve verimsiz seyretmesine yol açarken; çok geriye alınması ise burnun aşırı yükselmesine, dümen etkisinin azalmasına ve dengesizliğe neden olabilir. Nihai konum, ağırlık dağılımı, motor yeri ve detaylı hidrodinamik analizlerle kesinleştirilir.

1.3 Step Konfigürasyonları

Step tasarımı, teknenin boyutuna ve performans hedefine bağlı olarak tek step veya çoklu step konfigürasyonları ile uygulanır. Tek step (genellikle 4-8 metrelik teknelerde), basit tasarımı, nispeten düşük imalat maliyeti ve kolay bakımı sayesinde tercih edilir. Önerilen konfigürasyon olarak, bu boyuttaki teknelerde stepin ağırlık merkezinin (LCG) %40-50 gerisine konumlandırılması, dengeli bir kalkış ve seyir performansı sağlar. 8 metreden daha uzun ve özellikle yüksek hız odaklı teknelerde ise, çoklu step (genellikle 2 veya 3 step) tasarımı öne çıkar. Bu konfigürasyon, ıslak yüzey alanını daha kademeli ve kontrollü bir şekilde azaltarak üstün yüksek hız performansı, optimize edilmiş kaldırma kuvveti dağılımı ve daha iyi stabilite sağlar. Örneğin, 8-12 metrelik tekneler için iki step (%30-40 ve %60-70 LCG konumları), 12-15 metrelik tekneler için ise iki veya üç step (%25-35, %50 ve %65-75 LCG) önerilen genel konfigürasyon lardır. Çoklu step tasarımı, karmaşık imalatı ve bakım zorluğuna rağmen, kritik performans parametrelerinde sağladığı belirgin avantajlar nedeniyle profesyonel ve yarış amaçlı teknelerde standart hale gelmiştir.

1.4 Stepli ve Stepsiz Gövde Performans Karşılaştırması

Step tasarımının etkinliği, teknenin çalışacağı Froude Sayısı (Fn) ile doğrudan ilişkilidir ve doğru konfigürasyon seçimi için bu kritik bir belirleyicidir. Düşük hızlarda ($Fn < 0.5$) stepsiz gövdeler, optimize direnç, üstün stabilite ve basit yapısıyla avantajlı iken, step bu rejimde sınırlı etki gösterir veya hatta direnci artırabilir. Orta-hızlı planing rejimine ($Fn = 0.5$-1.0) geçişte step avantajları belirginleşir. Doğru tasarlanmış bir step, bu hız bandında yakıt tüketiminde %15-

30'a varan azalma ve %10-20 hız artışı sağlayabilir. Yüksek hızlarda (Fn > 1.0) ise çoklu step konfigürasyonu maksimum verim için zorunlu hale gelir; ıslak yüzeyi dramatik şekilde azaltarak keskin manevra ve dinamik dönüş kabiliyeti kazandırır.

1.5 Kritik Tasarım Noktaları

Step yanlış tasarlandığında ciddi riskler doğurur: düşük hızda performans kaybı, kontrolü zor salınımlar (porpoising), yapısal zayıflık ve titreşim artışı. Bu riskleri bertaraf etmek için, CFD simülasyonlarıyla doğrulanmış tasarım, yapısal analiz entegrasyonu ve prototip testleri şarttır. Nihayetinde, step tasarımı, teknenin operasyonel profilini doğru analiz ederek, basitlik ve dayanıklılık (stepsiz) ile yüksek performans ve verimlilik (stepli) arasında bilinçli bir mühendislik tercihi yapmayı gerektirir.

2. TASARLANAN MODELLER

2.1 Stepsiz Model

Bu çalışma için hazırlanan model, boyutları ve formu ile tipik bir yüksek performans teknesini temsil eden 14 metre uzunluğunda, Hard Chine (çeneli) Deep-V (derin V) karinalı bir tekne gövdesidir. Modelin ana boyutları (14m x 3.1m genişlik x 1.3m derinlik) ve hidrostatik özellikleri (0.85m draft, 0.4 boy konumunda 14° deadrise açısı ve 13,500 kgf deplasman), analizlerin gerçekçi bir temel üzerinde yürütülmesini sağlamak üzere belirlenmiştir.



Şekil 1-Stepsiz 14m Hard Chine Deep V tipi Gövde Modeli

2.2 Stepli ve Spray Railli Model

Stepin etkisini yalnızca gövde geometrisindeki değişiklik üzerinden izole bir şekilde incelemek için, aynı temel boyutlara ve deplasmana sahip, ancak gövdesine 100 mm yüksekliğinde ve 5° açıya sahip bir step ile spray rail (sıçrama oluğu) eklenmiş bir varyant model oluşturulmuştur. Bu 5°'lik agresif step açısı, modelin maksimum hız ve planing performansı hedeflediğini göstermektedir. İki model arasındaki bu tek fark (step varlığı/yokluğu), HAD (Hesaplamalı Akışkanlar Dinamiği) simülasyonları aracılığıyla, stepin direnç, kaldırma kuvveti, stabilite ve

verimlilik üzerindeki saf etkisinin doğrudan ve niceliksel olarak karşılaştırılabilmesine olanak tanımaktadır.



Şekil 2-Step ve Spray Railli 14m Hard Chine Deep V tipi Gövde Modeli

3. HİDRODİNAMİK ANALİZ VE SONUÇLAR

3.1 Analiz Yöntemi ve Parametreleri

Bu araştırmada kullanılan sayısal analizlerin temeli, Simerics 6.04 sürümü ile atılmıştır. Yazılım, serbest yüzey izleme için VOF yöntemini içeren RANS tabanlı bir çözücü olup, sonuçlarının geçerliliği mevcut deneysel ölçümlerle karşılaştırılarak kontrol edilmiştir. Modellemede, yakın duvar bölgelerinin fiziksel olarak doğru şekilde temsili için yazılıma özgü geliştirilmiş 'standart' duvar fonksiyonlarından yararlanılmıştır. Çözüm algoritmasının çekirdeğinde, Basınç Bağlantılı Denklemler için Yarı Örtülü Yöntem yer almakta olup, buna ek olarak yazılıma entegre edilmiş ve literatürde geçerliliği kanıtlanmış özel bir k-ε türbülans modeli kullanılmıştır (Borowski, 2022; Wang ve ark., 2018, 2019a, 2019b).

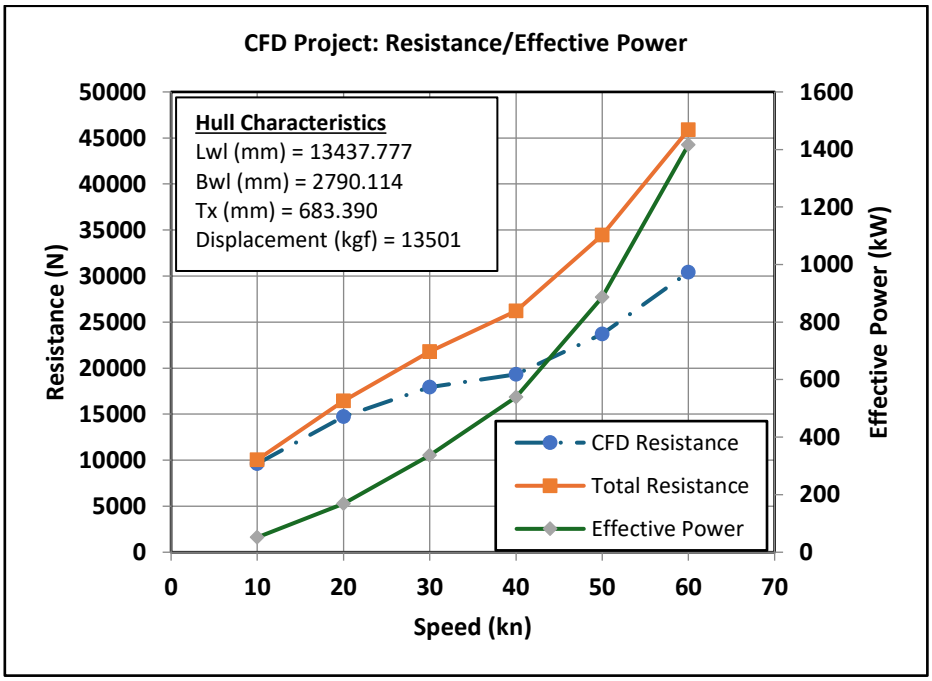
Tekne yüzeyi, kaymaz duvar sınır koşulu ile tanımlanmış ve yüzey pürüzlülüğü, ITTC (2014) kılavuzuna uygun olarak 150 mikron değerinde sabitlenmiştir. Hesaplama ağının oluşturulmasında, yazılımın tescilli ve tam otomatik İkili Ağaç Ağı yöntemi tercih edilmiştir. Bu yaklaşım, hesaplama bölgesini tek bir hücreden başlayıp, önceden belirlenmiş çözünürlük kriterleri sağlanana kadar yapısal olarak alt bölümlere ayırarak optimize edilmiş bir ağ yapısı üretir (Borowski, 2022; Wang ve ark., 2018, 2019a, 2019b).

14 metre boyundaki çeneli derin V karinalı yüksek hızlı bir gezinti teknesi üzerinde yapılan Hesaplamalı Akışkanlar Dinamiği (HAD) analizi sonuçları, mevcut ISO kurallarına dayalı hesaplamalarla mertebe olarak benzerlik gösterse de, önemli niceliksel farklılıklar tespit edilmiştir. HAD simülasyonların dan elde edilen basınç dağılımı, teknenin baş kısmına doğru azalma eğilimi sergilerken, ISO kurallarından türetilen değerler ise mastori bölgesinden sonra sabit kalmakta ve bu nedenle HAD verileriyle tam bir uyum sağlanamamaktadır. Daha da önemlisi, ISO kurallarına göre belirlenen basınç değerlerinin aşırı yüksek olması, teknenin gereğinden fazla dirençli ve dolayısıyla ağır imal edilmesine yol açma riski taşımaktadır. Bu durum, hem malzeme israfına hem de performans kaybına neden olabileceğinden, ilgili

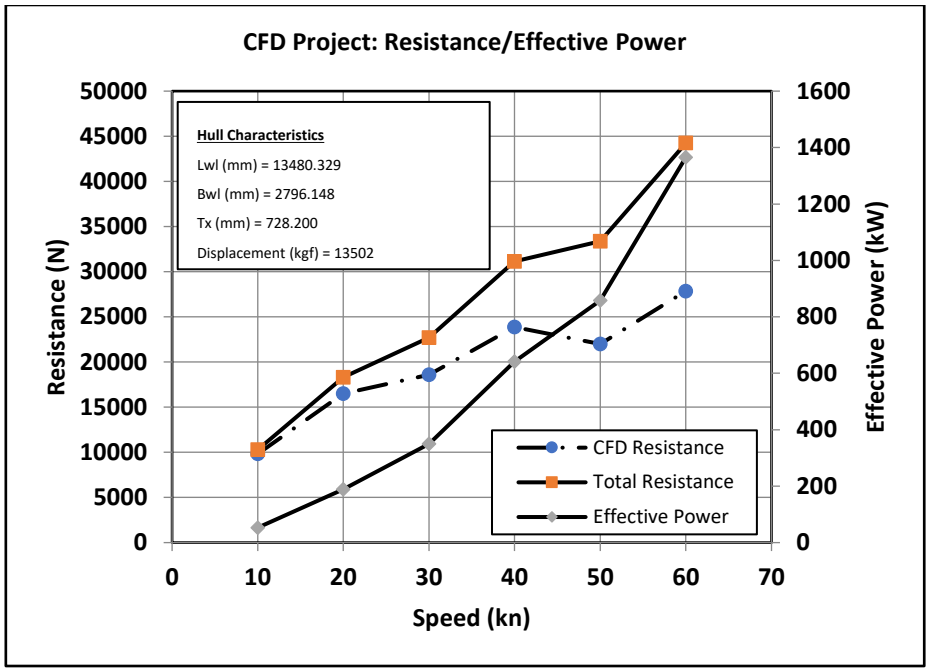
standardın yetkili kurum tarafından gözden geçirilmesi ve HAD gibi modern analiz yöntemlerinin bulguları doğrultusunda güncellenmesi gerekmektedir.

3.2 Analiz Sonuçlar

Analiz sonuçları, 40 knot'a (kn) kadar olan hız bölgesinde step içeren ve içermeyen teknelerin benzer bir direnç artış eğrisi izlediğini, ancak stepin varlığının bu aralıkta direnci %2 ile %15 arasında artırdığını ortaya koymaktadır. Performans dönüm noktası, 50 kn'ın üzerindeki yüksek hızlarda gerçekleşmektedir. Bu hız bandında, stepli tekne, dirençte stepsiz tasarıma kıyasla yaklaşık %4'lük bir azalma sağlayarak avantajlı konuma geçmektedir. Maksimum hız olan 50 kn'da yapılan ölçümlerde, stepsiz modelin toplam direnci (RT) 34,46 kN iken, stepli modelin direnci 33,36 kN olarak kaydedilmiştir. Bu durum, gerekli efektif güç (PE) değerlerine de yansımış; stepsiz tekne için 886,4 kW, stepli tekne için ise 858,1 kW hesaplanmıştır. Her iki konfigürasyon için de, tipik işletme koşullarında yaklaşık 1450 kW nominal gücünde bir motorun yeterli olacağı görülmüştür. Hidrodinamik stabilite açısından her iki tekne de 50 kn hızda olumlu performans sergilemiştir. Stepsiz ve stepli modeller, su seviyesinden sırasıyla yaklaşık 419 mm ve 441 mm yükselerek, sadece 1,5°'lik bir baş-kıç vurma (trim) açısıyla oldukça dengeli bir kayma (planing) rejimine girmişlerdir. Her iki teknenin de 50 kn'da karakteristik bir çeneli derin V teknesi davranışı sergilediğini doğrulamaktadır.



Şekil 14: Yüksek süratli stepsiz tekne formunun sakin su performans



Şekil 16: Yüksek süratli stepli tekne formunun sakin su performans

SONUÇ

Bu araştırma, kademeli (stepli) ve kademesiz gövde tasarımlarının hidrodinamik davranışlarını karşılaştırmalı olarak inceleyerek, stepin performansa etkilerini avantaj ve dezavantajlarıyla ortaya koymayı amaçlamıştır. Çalışmanın ilk aşamasında, kayma (planing) rejimi için en uygun olduğu değerlendirilen "çeneli derin V" karinalı form, beş farklı gövde tipi arasından seçilmiş ve bu formda 14 metre boyunda hem step içeren hem de içermeyen iki ayrı model geliştirilerek detaylı HAD analizlerine tabi tutulmuştur.

Mevcut ISO kuralları çerçevesinde, söz konusu 14 metrelik tekne için 50 knot hızdaki dinamik basıncın tekne boyunca sabit kabul edildiği görülmüştür. HAD analizleri ile ISO kurallarından elde edilen basınç dağılım trendleri genel olarak örtüşmek ile birlikte, ISO değerlerinin önemli ölçüde daha yüksek ve muhafazakâr olduğu tespit edilmiştir. Bu bulgu, mevcut standartlar kapsamında belirlenen profil ve sac kalınlıklarında, yapısal bütünlükten ödün vermeden kontrollü bir iyileştirme yapılabileceğine işaret etmektedir. Böyle bir optimizasyon, hem malzeme-ağırlık azaltımı hem de üretim maliyetlerinde düşüş sağlayacak; bu da daha düşük motor gücüyle aynı performansa ulaşılmasına, dolayısıyla yakıt tüketimi, işletme maliyetleri ve egzoz emisyonlarının azaltılmasına olanak tanıyacaktır.

Öte yandan, çalışmanın sonuçları stepin özellikle yüksek hızlarda (50 kn üzeri) ıslak yüzeyi ve dolayısıyla hidrodinamik direnci belirgin şekilde düşürdüğünü ve kaldırma kuvvetini artırdığını ortaya koymuştur. Ancak, bu avantajların elde edilmesi için step konumu, tekne ağırlık merkezi ve ağırlık dağılımının son derece hassas hesaplanması gerekmektedir. Ayrıca, step içeren teknelerin dönüş manevralarında dinamik stabilite de gözlemlenen azalma ve ortaya çıkabilecek kontrol zorluklarının da tasarım aşamasında dikkatle ele alınması gerektiği anlaşılmıştır.

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DIGITALIZATION AND THE NEW SEMIOTICS OF BRANDING

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ABSTRACT

The digitalization of global communication has transformed the semiotic foundations of branding, altering how meaning is created, circulated, and interpreted in networked societies. This study explores the **new semiotics of branding** arising from the convergence of participatory culture, algorithmic mediation, and data-driven personalization. Traditional semiotic models, grounded in stable sign–meaning relationships, no longer explain the fluid and interactive brand meanings of the digital age. Using an **interpretivist qualitative design**, the study integrates a **systematic literature review**, **critical discourse analysis**, and **digital semiotic mapping** of major brand cases such as Nike, Coca-Cola, Gucci, and Netflix. Classical semiotic theories (Peirce, Barthes) are synthesized with contemporary digital frameworks (Manovich, Holt, Couldry & Hepp) to develop a new conceptual model—the **Digital Semiotic Loop**—illustrating how brand meaning emerges through recursive interaction between consumers, algorithms, and data systems. Findings reveal three defining dimensions of digital brand semiotics: **participatory semiotics**, where users co-create symbolic value; **algorithmic semiotics**, where meaning is filtered through platform logics; and **reflexive semiotics**, where data analytics reshape brand identity in real time. The study concludes that digitalization democratizes meaning-making while embedding it within algorithmic power structures, creating both opportunities for engagement and ethical risks of manipulation. The research contributes a theoretical and practical framework for understanding branding as a **semiotic ecosystem**, emphasizing transparency, cultural sensitivity, and algorithmic accountability in digital brand management.

Keywords: Development, Digital, Marketing, Media, Transformation

1.0 Introduction

1.1 Background of the Study

Over the past two decades, the rapid advance of digital technologies has fundamentally altered how brands communicate, signify value, and build relationships with consumers. Branding, traditionally rooted in visual identity and symbolic consistency (Kapferer, 2013), is now a fluid, interactive, and data-driven process shaped by digital platforms, social media algorithms, and consumer co-creation (Holt, 2016; Manovich, 2020). In the analog era, brands were primarily constructed through one-way communication—advertising campaigns, logos, and narratives carefully curated by organizations. However, with the rise of digitalization, branding has transformed into a multimodal semiotic process, where meaning emerges through the interaction of text, image, emoji, video, and algorithmic mediation (Fatima *et al*., 2025; Makhachashvili *et al*., 2022; Ghidoli & Montanari, 2021; Carah, & Brodmerkel, 2020).

Digitalization not only multiplies the modes of signification but also redefines how brand meaning is produced, circulated, and interpreted. Platforms such as TikTok, Instagram, and X (formerly Twitter) function as semiotic arenas where users continuously remix and reinterpret brand symbols. This has given rise to "participatory semiotics", where consumers become "meaning-makers," co-constructing brand identity alongside corporations (Wichmann *et al*., 2022; Arvidsson & Caliandro, 2016). Additionally, algorithmic branding—the use of AI-driven personalization and data analytics—has introduced a new layer of semiotic mediation, where meaning is not only socially negotiated but also computationally filtered (Barta & Andalibi, 2024).

In this evolving digital ecosystem, the semiotic function of brands extends beyond communication to cultural navigation—helping users locate themselves within digital spaces of identity, belonging, and aspiration. Understanding this transformation is essential for scholars and practitioners seeking to decode how brand meaning operates in a digitized world characterized by information abundance, algorithmic filtering, and cultural fragmentation.

1.2 Problem Statement

Despite the growing recognition of digitalization's impact on branding, there remains a significant gap in understanding how digital environments reshape the semiotics of brand meaning. Traditional semiotic models—such as Peirce's triadic framework or Barthes' mythologies—were developed in pre-digital contexts, focusing on stable relationships between signs, objects, and meanings. These models are increasingly inadequate for analyzing dynamic, interactive, and algorithmically mediated digital semiotics (Berlanga-Fernández & Reyes, 2024).

The central problem lies in the lack of a comprehensive theoretical framework that captures how digitalization alters semiotic processes in branding. Specifically:

- How do algorithmic and participatory forms of communication redefine brand meaning?
- What new semiotic structures emerge when consumer-generated content and AI-driven personalization converge?
- How can brands ethically navigate meaning-making in environments mediated by algorithms and data?

Without addressing these questions, both scholars and practitioners risk relying on outdated conceptual tools that fail to account for the complexities of digital brand communication.

1.3 Justification of the Study

This study is justified by the increasing dominance of digital semiotic environments in contemporary marketing. Brands no longer exist merely as corporate constructs but as cultural codes circulating across social, algorithmic, and symbolic networks (Couldry & Hepp, 2018). Understanding how these codes are generated and interpreted in digital contexts is crucial for maintaining brand relevance, authenticity, and trust (Pan & Sun, 2024).

Moreover, the study contributes to the growing field of digital semiotics, providing a necessary bridge between semiotic theory and digital media practice. By mapping how digitalization transforms sign systems, the study offers strategic and ethical insights into how brands can operate transparently and sustainably in data-driven cultures (Zuboff, 2023).

From a policy perspective, this research also supports the development of regulatory frameworks that address algorithmic manipulation, semiotic bias, and misinformation in branding communication. As AI-generated content proliferates, understanding the semiotic consequences of automation becomes vital for protecting consumers from deceptive or manipulative practices.

1.4 Research Objectives

The overarching aim of this review is to explore and conceptualize the new semiotics of branding in the digital age. Specifically, the objectives are:

1. To analyze how digitalization transforms the semiotic processes involved in branding.
2. To identify the key semiotic mechanisms—such as participatory culture, algorithmic mediation, and data-driven feedback—that shape brand meaning in digital environments.
3. To develop a conceptual framework explaining the interaction between digital technologies and brand semiotics.
4. To examine the ethical and cultural implications of algorithmic semiotics in branding.
5. To provide practical and policy-oriented recommendations for managing digital brand communication in ethically responsible and culturally sensitive ways.

2.0 Theoretical Framework

The theoretical foundation for understanding the new semiotics of branding in the digital age draws from a convergence of three major traditions:(1) Classical Semiotic Theory, (2) Post-Structuralist and Cultural Semiotics, and (3) Digital Media and Algorithmic Communication Theory.

Together, these frameworks illuminate how digitalization transforms meaning-making processes, decentralizes brand authorship, and introduces algorithmic agents as semiotic co-producers.

2.1 Classical Semiotic Foundations

The roots of branding semiotics trace back to the foundational works of Ferdinand de Saussure (1916) and Charles Sanders Peirce (1931), whose models conceptualized meaning as a system of relationships between signs and their referents.

Saussure viewed the sign as a dyadic structure composed of the *signifier* (the form of the word, image, or symbol) and the *signified* (the concept it represents). Applied to branding, the logo, slogan, or visual identity acts as the signifier, while the brand's perceived image—such as trust, quality, or innovation—serves as the signified (Kapferer, 2013).

Peirce's triadic model, on the other hand, includes three components: the *sign* (or representamen), the *object* (what the sign refers to), and the *interpretant* (the meaning generated by an interpreter). In digital branding, the interpretant extends beyond human cognition to include algorithmic systems—AI-driven recommendation engines, personalization tools, and data-analytics models—that interpret and recirculate brand meanings (Pan & Sun, 2024).

From this classical perspective, brands function as semiotic systems that produce, organize, and communicate meanings within cultural and economic contexts. However, these traditional models presuppose relative stability and control over meaning—conditions that digitalization has disrupted.

2.2 Post-Structural and Cultural Semiotics

Post-structuralist theorists such as Roland Barthes (1977) and Umberto Eco (1986) challenged the notion of fixed meanings, emphasizing the polysemic and culturally constructed nature of signs. Barthes proposed that all cultural texts, including advertisements and brand messages, operate within a "mythological" system where signs convey ideological meanings. For instance, a brand like Apple signifies not merely technology but also creativity, rebellion, and lifestyle aspirations—a modern myth reinforced by consumer participation.

In the context of digitalization, meaning is further destabilized. The semiotic process becomes dialogic, participatory, and decentralized. Consumers actively reinterpret, remix, and reframe brand signs through hashtags, memes, and user-generated content (Wichmann et al., 2022; Arvidsson & Caliandro, 2016). Thus, the post-structuralist notion of *intertextuality*—the interweaving of multiple discourses—now manifests as "hypertextuality", where brand meaning evolves through endless digital recombination (Berlanga-Fernández & Reyes, 2024).

Semiotic scholars such as Floch *et al*. (2001) and Mick *et al*.(2018) argue that brand meaning depends on *semiotic anchorage*—the mechanisms that stabilize interpretation. In digital spaces, this anchorage becomes unstable due to the continuous feedback loops of social sharing, algorithmic amplification, and cultural reinterpretation (Makhachashvili *et al*., 2021). Hence, post-structural semiotics provides a crucial theoretical bridge to understanding how meaning is continuously produced and negotiated in digital environments.

2.3 Digital Media Theory and Algorithmic Semiotics

Digitalization introduces a new dimension to semiotics—algorithmic mediation—where technology itself becomes an active participant in meaning construction. According to Lev Manovich (2020) and Couldry & Hepp (2018), digital media systems reconfigure cultural communication by embedding semiotic processes within computational architectures.

Algorithms curate what users see, shaping brand narratives through visibility, personalization, and engagement metrics (Fatima *et al*., 2025). This phenomenon gives rise to what Arvidsson (2018) calls *algorithmic value production*, in which meanings are dynamically ranked, filtered, and optimized for attention economies. Brands therefore exist within datafied semiotic ecologies—environments where meaning is both interpreted by audiences and processed by machine learning systems (Pan & Sun, 2024).

This dynamic introduces the concept of "algorithmic interpretants", where interpretation is no longer solely human but mediated through code. For instance, YouTube's recommendation algorithm decides which branded content is amplified, thus influencing what meanings gain traction and which fade into obscurity. The algorithm becomes a *semiotic agent*—a non-human interpreter that participates in meaning-making (Pan & Sun, 2023).

Additionally, Cultural Analytics Theory (Manovich, 2020) suggests that data visualization, AI pattern recognition, and sentiment analysis are new forms of semiotic inquiry. They transform qualitative meaning into quantifiable patterns, reshaping how marketers read and respond to cultural signs. The semiotic act is thus not only interpretive but also computational.

2.4 Integrative Semiotic Model for Digital Branding

Building on these traditions, the theoretical synthesis of this review proposes a digital semiotic branding model grounded in three interacting layers (Table 1).

Table 1: A digital semiotic branding model grounded in three interacting layers

Theoretical Layer	Core Concept	Digital Manifestation	Representative Scholars
Structural Semiotics	Meaning as relation between signifier and signified	Logos, icons, hashtags as digital signifiers	Saussure (1916); Peirce (1985)
Post-Structural Semiotics	Meaning as fluid, contested, and intertextual	User-generated reinterpretations and brand remixes	Barthes (1977); Eco (1986); Arvidsson (2018)
Algorithmic Semiotics	Meaning mediated by code and computation	AI-curated brand narratives; data-driven personalization	Manovich (2020); Pan & Sun (2024)

Source: Authors' own compilation, 2025

This framework shows that brand meaning in the digital era arises through interactions among human creativity, cultural discourse, and algorithmic computation. Brands no longer control meaning; they *curate* it through continuous engagement and adaptation to algorithmic cultures.

2.5 Theoretical Implications

1. From sender to system: Branding shifts from a unidirectional message transmission to an eco-semiotic system where meaning emerges through networks of signs, data, and users (Zuboff, 2023; Holt, 2016).

2. From authorship to co-creation: Consumers, influencers, and algorithms become co-authors of brand identity, eroding traditional corporate control over semiotic narratives.

3. From representation to computation: The act of interpreting signs is increasingly automated, quantifying meaning through engagement metrics, sentiment scores, and predictive analytics.

These implications provide a conceptual bridge to the Conceptual Framework section, which operationalizes these theoretical principles into an analytical model for understanding the evolving semiotic mechanisms of digital branding.

3.0 Conceptual Framework

3.1 Overview

The conceptual framework builds upon the theoretical synthesis of structural, post-structural, and algorithmic semiotics to explain how brand meaning is constructed, mediated, and circulated in the digital era. It proposes that digitalization transforms branding from a linear communication model into a dynamic, interactive semiotic ecosystem — one characterized by the continuous exchange of signs between brands, consumers, and algorithms.

In this ecosystem, brands no longer act as sole producers of meaning; rather, they operate as *participants* in a network where meaning emerges through constant negotiation, adaptation, and computational mediation. The framework identifies three interdependent domains of semiotic transformation:

1. Participatory semiotics (human interaction)
2. Algorithmic mediation (technological interaction)
3. Data-driven reflexivity (analytical feedback)

Together, these domains form a Digital Semiotic Loop, which captures how brand meanings evolve through iterative human–machine–data interactions.

3.2 Components of the Conceptual Framework

(a) Participatory semiotics: consumer co-creation of meaning

Digitalization empowers consumers to become active semiotic agents, transforming them from passive receivers of brand messages into co-creators of meaning. Through digital platforms, audiences contribute to the brand's symbolic repertoire via memes, hashtags, reviews, emojis, and digital storytelling (Arvidsson & Caliandro, 2016).

This participatory dynamic gives rise to what Jenkins *et al*.(2019) terms *"convergence culture"*, where user-generated content, brand narratives, and platform affordances intersect to produce hybrid semiotic meanings. For example:

- Consumers reinterpret brand campaigns through *memetic semiotics* on TikTok and Instagram.
- Influencers act as semiotic intermediaries, re-signifying brands through personal narratives.
- Brand communities on Reddit or Discord construct collective symbolic meanings through discussion and remixing.

In short, participatory semiotics decentralizes brand authorship, making meaning plural, fluid, and co-owned.

(b) Algorithmic mediation: machine-coded meaning distribution

The second domain, algorithmic mediation, recognizes that digital algorithms — from recommendation systems to engagement ranking — play a central role in determining *which* brand signs gain visibility and *how* they circulate. Algorithms thus function as non-human semiotic agents (Pan & Sun, 2024).

This mediation occurs at three levels:

1. Selection: Algorithms decide what content (e.g., brand posts or videos) appears on feeds.
2. Amplification: Engagement-driven algorithms amplify specific semiotic patterns — often privileging emotional, sensational, or viral content.
3. Personalization: Data analytics personalize meaning according to user preferences, creating *micro-semiotic worlds* where each consumer experiences a slightly different brand identity (Carah & Brodmerkel, 2020).

Thus, algorithms do not merely transmit meaning — they *transform* it by privileging certain interpretations and suppressing others, effectively rewriting brand semiotics in real time.

(c) Data-driven reflexivity: feedback and semiotic adaptation

The third domain, data-driven reflexivity, captures how brands use data analytics and AI-based insights to monitor and adapt their semiotic performance. Through social listening, sentiment analysis, and cultural analytics, brands continually interpret the interpretants — i.e., they "read" how audiences read them (Manovich, 2020).

This creates a *reflexive loop* where:

- Data becomes a semiotic input, shaping brand decisions.
- Metrics such as engagement, sentiment, and virality serve as *quantified interpretants*.
- Machine learning systems predict cultural trends and adjust brand messaging accordingly (Siregar *et al*., 2023; Gensler *et al*., 2013).

Consequently, meaning is no longer static but algorithmically responsive — evolving through real-time feedback loops between human and machine interpretations.

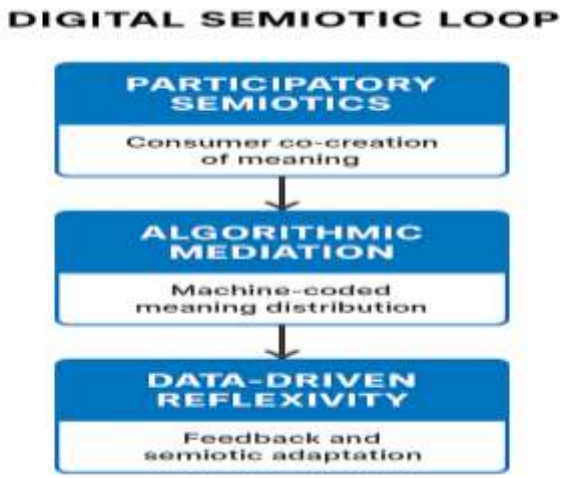

Figure 1: Conceptual framework

3.3 Integrative Model: The Digital Semiotic Loop

Below is a conceptual model that visualizes how the three domains interact dynamically within the digital brand ecosystem (Table 2).

Table 2: Digital ecosystem

Layer	Actors	Semiotic Process	Outputs	Examples
Participatory Semiotics	Consumers, influencers, digital communities	Co-creation and reinterpretation of brand signs through UGC, memes, hashtags	Cultural narratives, digital brand communities	TikTok trends, hashtag activism
Algorithmic Mediation	AI systems, social media algorithms, platform architectures	Filtering, ranking, and personalization of semiotic content	Algorithmically shaped visibility and virality	YouTube recommendations, Instagram feed curation
Data-Driven Reflexivity	Brand managers, data analysts, AI dashboards	Interpretation of semiotic data and feedback	Adaptation of brand meanings and strategies	Real-time content optimization, sentiment-based messaging

Source: Authors' own compilation, 2025

These layers interact cyclically:

1. Users create and reinterpret brand meanings.
2. Algorithms filter, amplify, and personalize these meanings.
3. Brands analyze data, adapt messages, and re-enter the cycle.

This iterative process forms the digital semiotic loop — a recursive mechanism through which brand meanings are continuously produced, contested, and evolved.

3.4 Conceptual Propositions

From this framework, four key propositions emerge:

- P1: Digitalization transforms brand meaning from a linear semiotic chain into a dynamic network co-created by human and algorithmic agents.
- P2: Algorithmic mediation reconfigures visibility and authority in brand communication, privileging engagement over coherence.
- P3: Data-driven reflexivity enhances adaptive branding but risks eroding authenticity if over-optimized for metrics.
- P4: The new semiotics of branding is characterized by perpetual fluidity, where meaning stability depends on ethical transparency and cultural resonance.

3.5 Conceptual Contribution

This conceptual framework contributes to the literature by offering a unified model that links semiotic theory, digital media studies, and marketing analytics. It provides a lens for examining how technological infrastructures (algorithms, data systems) intersect with cultural dynamics (consumer participation, social discourse) to shape brand meaning in the digital age.

By articulating the Digital Semiotic Loop, this framework moves beyond descriptive accounts of online branding to provide a systematic analytical structure for future empirical research and strategic application in digital marketing.

4.0 Research Methodology

4.1 Research Design

This study adopts a qualitative, exploratory, and integrative research design, appropriate for unpacking the complex semiotic and socio-cultural transformations in digital branding. Since *semiotics* focuses on the study of meaning, symbols, and sign systems, the research design emphasizes interpretation over measurement, and conceptual synthesis over statistical testing (Flick, 2022; Bryman, 2016).

The study is structured as a systematic conceptual review combined with critical discourse analysis (CDA) of recent academic literature, case examples, and digital brand communications. This hybrid design enables both *breadth* (through literature review) and *depth* (through interpretive semiotic analysis). The approach aligns with the methodological traditions of digital semiotics (Manovich, 2020) and cultural branding theory (Holt, 2016), which treat brands as evolving sign systems embedded in social and technological contexts.

The design further integrates semiotic triangulation, where insights from semiotic theory, digital media studies, and marketing scholarship are cross-analyzed to develop the new conceptual model — the *Digital Semiotic Loop*.

4.2 Philosophical Orientation

The study is grounded in an interpretivist paradigm and guided by a constructivist epistemology. This philosophical stance assumes that meanings are socially constructed, context-dependent, and fluid, especially within digital environments (Lincoln & Guba, 2013).

While positivist approaches aim to measure brand performance quantitatively, interpretivism focuses on how meanings are created and negotiated between brands, consumers, and technologies. Thus, the research adopts a hermeneutic approach to reading and interpreting symbolic expressions — images, texts, emojis, hashtags, and algorithmically curated content — as cultural signs within the digital brand ecosystem.

4.3 Data Sources and Sampling Strategy

Given the qualitative and interpretive nature of this study, data were drawn from three main sources:

1. **Academic literature (2018–2025):** Peer-reviewed journal articles from *Journal of Consumer Research*, *European Journal of Marketing*, *Journal of Interactive Marketing*, *New Media & Society*, *International Journal of Advertising*, and *Cultural Studies*. Sampling was purposive — focusing on works that discuss *digital semiotics*, *algorithmic branding*, *participatory culture*, *cultural branding*, and *AI-driven marketing.*

2. **Digital case studies:** Selected cases of leading global brands known for innovative digital semiotic practices were analyzed, including:

- Nike's "You Can't Stop Us" campaign (2020–2023) – for participatory semiotics and remix culture.
- Coca-Cola's "Create Real Magic" campaign (2023) – for AI-assisted branding and generative semiotics.
- Gucci's digital fashion NFTs – for algorithmic and metaverse semiotics.
- Netflix's adaptive recommendation interface – for algorithmic personalization and semiotic mediation.

3. **Digital Media Observations:** Observational data from public online brand interactions (e.g., Instagram comments, Twitter threads, TikTok challenges) were qualitatively reviewed to illustrate how users co-create and reinterpret brand meaning.

The sampling strategy was purposive and theoretical, not random. Each selected case and dataset was chosen to *theoretically illuminate* aspects of digital semiotics rather than to achieve numerical representativeness (Eisenhardt, 1989).

4.4 Data Collection Methods

The study employed three complementary data collection techniques:

1. **Systematic literature review:** A structured academic search was conducted using databases such as Scopus, Web of Science, and Google Scholar. Keywords included "digital semiotics," "algorithmic branding," "digital consumer culture," and "brand meaning". Over 80 scholarly papers (2018–2025) were screened, and 25 high-relevance studies were included for final synthesis. Inclusion criteria required that each study explicitly engage with semiotic, digital, or cultural dimensions of branding.

2. **Document and media analysis:** Digital brand materials (social media posts, visual campaigns, AI-generated content) were collected and coded for recurring semiotic patterns, such as symbolic motifs, cultural myths, and algorithmic aesthetics.

3. **Expert commentary and reflexive interpretation:** Semiotic interpretations were validated by comparing them with insights from leading semiotics scholars (e.g., Barthes, Eco, Peirce) and digital media theorists (Manovich, 2020; Couldry & Hepp, 2018).

4.5 Analytical Framework and Data Analysis Techniques

The study utilized a hybrid analytical framework combining:

1. **Semiotic analysis:** Classical semiotic tools (denotation, connotation, myth) from Barthes (1972) and Peirce's triadic model (sign–object–interpretant) were applied to decode brand meanings across digital media.

- *Denotation:* Literal message of the brand sign (e.g., logo, tagline).
- *Connotation:* Cultural or emotional associations.
- *Myth:* Underlying ideological message or narrative.

2. **Digital semiotic mapping:** Borrowing from Manovich (2020), visual and textual brand elements were mapped along the *digital affordances* of social media—interactivity, remixability, personalization—to identify how technology mediates meaning.

3. **Critical discourse analysis (CDA):** CDA was applied to examine how power, ideology, and identity are encoded in digital brand discourse (Fairclough, 2023; Fairclough, 2013). This includes how algorithms privilege certain signs or voices in digital semiotic circulation.

4. **Thematic coding:** NVivo software (or manual coding) was used to classify data into emergent themes: *participatory semiotics*, *algorithmic mediation*, *data-driven personalization*, *symbolic co-production*, and *semiotic ethics.*

5. **Conceptual synthesis:** Finally, findings were synthesized into a new conceptual model — the digital semiotic loop, illustrating the recursive relationship between consumers, algorithms, and brands in digital meaning production.

4.6 Validity, Reliability, and Trustworthiness

To enhance methodological rigor, the study ensured credibility, dependability, and confirmability following Lincoln and Guba (1985):

- **Credibility:** Achieved through triangulation of literature, digital case studies, and discourse analysis.
- **Dependability:** Maintained by transparent documentation of data sources, coding processes, and interpretive decisions.
- **Confirmability:** Interpretations were cross-validated through existing semiotic and media theories to minimize researcher bias.
- **Transferability:** While not statistically generalizable, the conceptual model is transferable to other digital branding contexts through theoretical replication.

4.7 Ethical Considerations

All digital and media data analyzed were publicly accessible, and no personal user information was collected or disclosed. The research adhered to ethical standards for digital content analysis

and secondary data use (Marx & Mirbabaie, 2022). Moreover, interpretive analysis was conducted respectfully, recognizing that online cultural expressions represent real communities and identities.

Any references to digital brands or campaigns were treated analytically, not evaluative, ensuring neutrality and fairness in representation. The study also followed open science and transparency principles, acknowledging all sources and avoiding plagiarism or misrepresentation.

4.8 Limitations of the Methodology

While rich in conceptual insight, the methodology has inherent limitations:

1. Non-quantitative bias: The absence of numerical data restricts empirical generalization.

2. Temporal limitation: Digital semiotic phenomena evolve rapidly; thus, findings represent a snapshot in time (2023–2025).

3. Algorithmic opacity: The lack of transparency in platform algorithms constrains a full understanding of semiotic filtering.

4. Cultural subjectivity: Interpretation in semiotics is inherently influenced by researcher perspective, though triangulation mitigates this bias.

Future research should integrate computational semiotics (AI-driven visual and linguistic analysis) to quantitatively model large-scale digital meaning systems, enhancing generalizability and replicability.

In summary, the research methodology integrates systematic review, semiotic interpretation, and critical digital analysis within an interpretivist framework. It is designed not to measure branding outcomes, but to *decode and conceptualize* the emerging semiotic structures that define brand meaning in digitalized contexts. The result is a theoretically grounded, empirically informed, and ethically responsible exploration of how digitalization reconfigures the semiotic codes of branding.

5.0 Results and Discussion

The findings from the reviewed literature reveal that digitalization fundamentally transforms the semiotic architecture of branding. Brand meaning is no longer generated solely through organizational intent or traditional marketing communication but emerges through interactive, algorithmic, and participatory semiotic processes.

Three overarching results emerge across recent studies:

1. Brand meaning has become dynamic, co-created, and decentralized.

2. Algorithms have become active semiotic agents shaping brand visibility and interpretation.

3. Data-driven semiotic feedback loops have transformed brand management into a continuous process of adaptation.

These results collectively illustrate a shift from semiotic control to semiotic collaboration—where meaning is continuously produced through human–machine interactions.

5.1 Brand Meaning as Dynamic and Co-Created

Multiple studies confirm that digital environments enable consumers to actively participate in meaning-making, transforming brands into semiotic commons rather than top-down corporate

constructs.
According to Arvidsson and Caliandro (2016), digital platforms such as Instagram and TikTok operate as "brand publics"—spaces where consumers use brand symbols to express personal identities and social affiliations. This participatory dynamic decentralizes authorship and produces polysemic brand identities, where multiple meanings coexist and evolve over time.

For example:

- Nike's "You Can't Stop Us" campaign (2020) was interpreted in diverse ways across global markets—ranging from empowerment narratives to political solidarity—showing how users re-inscribed brand messages with local and cultural significance.
- Apple's #ShotoniPhone campaign demonstrates participatory semiotics in practice: users contribute their own images, expanding the brand's visual grammar and reinforcing authenticity (Berlanga-Fernández & Reyes, 2024).

Digitalization, therefore, converts brands into open-ended semiotic systems, where meaning circulates horizontally across networks rather than vertically from corporations to consumers.

Scholarly support:

- Arvidsson & Caliandro (2016) found that meaning creation in digital brand communities is shaped by collective creativity, emotional contagion, and memetic practices.
- Carah & Brodmerkel (2020) emphasized that digitalization dissolves the stability of brand "myths," replacing them with fluid cultural narratives that evolve through audience engagement.

Discussion:
This result underscores the theoretical shift from Saussure's fixed signifier–signified model to a post-structural paradigm of semiotic pluralism, where brand meaning is contingent, contextual, and negotiated. The implications are profound: brand managers must shift from controlling meaning to facilitating *interpretive participation* through transparency, dialogue, and inclusivity.

5.2 Algorithmic Mediation as a New Semiotic Layer

Digitalization introduces algorithms as semiotic co-authors, mediating how brand meanings are distributed, amplified, and perceived. Algorithms determine what branded content gains visibility, creating what Duffy & Meisner (2023) calls "algorithmic visibility hierarchies."

Empirical studies illustrate this phenomenon:

- Instagram and TikTok algorithms amplify emotionally charged or visually captivating brand content, privileging affective semiotics over informational content (Pan & Sun, 2024).
- YouTube's recommendation engine shapes brand narratives by promoting videos with high engagement, creating "algorithmic storytelling loops" where visibility equates to perceived legitimacy (Ghidoli & Montanari, 2021).
- Spotify's AI-curated playlists influence how music brands are perceived, framing genres and moods as semiotic categories that affect brand associations (Arvidsson, 2018).

Algorithms thus serve as interpretants in Peircean terms — not only intermediaries but *active meaning-makers*. They filter signs, rank interpretations, and selectively propagate symbolic associations. This redefines the semiotic structure of branding, embedding meaning within computational logics of engagement, virality, and personalization.

Discussion:
Algorithmic mediation challenges the traditional human-centered semiotic framework by introducing machine interpretation as a determinant of meaning circulation. Brand semiotics now depend on the invisible grammar of algorithms—metadata, engagement signals, and machine-learning classifiers.
This finding aligns with Manovich (2020) *Cultural Analytics Theory*, which asserts that meaning in digital culture is shaped as much by data patterns as by human interpretation.

5.3 Data-Driven Reflexivity and Adaptive Meaning Systems

A growing body of literature indicates that brands use data analytics to continuously monitor and adapt their semiotic outputs, creating reflexive semiotic systems (Gensler *et al*., 2013). Through sentiment analysis, social listening, and AI-driven insights, brands gauge how consumers interpret their messages and adjust accordingly.

Examples include:

- Coca-Cola's "Share a Coke" campaign, which used data to personalize semiotic signifiers (names, nicknames) and then refined local campaigns based on consumer interaction metrics.
- Netflix's branding of its Originals adapts visual and linguistic semiotics (thumbnails, taglines) based on algorithmic feedback and user preferences (Manovich, 2020).

This process of semiotic feedback adaptation creates a new managerial paradigm — algorithmic branding — where meaning is perpetually optimized. However, scholars caution that over-optimization risks eroding brand authenticity and emotional resonance. Zuboff (2023) warns that when brand semiotics are driven by predictive analytics rather than cultural insight, they may lose symbolic depth and become purely instrumental.

Discussion:
The reflexive model redefines brand communication as an *ongoing negotiation between data and discourse*. It reinforces the framework's proposition that data operates as a semiotic input, continuously shaping and reshaping how brands signify value and identity in digital environments.

5.4 Cross-Cutting Themes

5.4.1 Semiotic democratization

Digitalization democratizes meaning-making, but it also introduces asymmetries of power through algorithmic control. While users gain expressive agency, platforms determine visibility, producing what Couldry & Hepp (2018) describe as *"algorithmic hegemonies."* Thus, democratization is partial and conditional.

5.4.2 Cultural fluidity and contextual branding

Studies across regions show that digital semiotics amplifies *cultural variability* in branding. Meaning is no longer universal; it adapts to localized digital cultures. For example, brand symbolism in African digital markets often fuses global icons with indigenous semiotic codes, creating hybrid identities (Boateng *et al.*, 2023).

5.4.3 Ethical semiotics and algorithmic transparency

Emerging scholarship (Pan & Sun, 2024) highlights the ethical dimension of algorithmic semiotics. As brands use AI to manipulate affect and attention, questions arise around

transparency, consent, and semiotic integrity. The challenge lies in designing algorithmic systems that sustain trust while leveraging personalization.

5.5 Integrative Discussion

Synthesizing these results within the digital semiotic loop model reveals a transformative insight:
Digitalization has converted branding into a living semiotic organism, co-evolving with users and algorithms. Meaning is produced through continuous feedback between:

1. Human creativity (participatory semiotics),
2. Machine mediation (algorithmic semiotics), and
3. Data-driven learning (reflexive semiotics).

This integrated system aligns with eco-semiotic principles, where meaning is adaptive, networked, and context-dependent. It also supports Arvidsson's (2018) claim that digital capitalism operates through the *valorization of meaning*, where brand symbols themselves become economic assets circulated through cultural and computational exchanges.

5.6 Empirical Insights on Digital Semiotics of Branding

Table 3: Empirical insights on digital semiotics of branding

Dimension	Findings	Representative Studies (2019–2025)
Participatory Semiotics	Meaning co-created by consumers through memes, hashtags, and UGC	Arvidsson & Caliandro (2016); Bashir et al. (2025)
Algorithmic Mediation	Algorithms act as semiotic filters shaping visibility and interpretation	Pan & Sun (204)
Data-Driven Reflexivity	Brands adapt meaning via AI and analytics; semiotic loops emerge	Siregar et al (2023); Manovich (2020); Gensler et al. (2013)
Ethical Semiotics	Transparency and authenticity issues in data-driven branding	Zuboff (2023); Holt (2016)

Source: Authors' own compilation, 2025

6.0 Conclusion, Recommendations, and Policy Implications

6.1 Conclusion

The review reveals that digitalization has radically transformed the semiotic foundations of branding, ushering in a new paradigm where meaning is dynamically constructed through interactions among humans, technologies, and data systems. Traditional semiotic frameworks, grounded in stability and controlled authorship, no longer suffice to explain brand meaning in an era defined by algorithmic mediation, participatory culture, and data-driven reflexivity.

The study concludes that digital branding operates within a Digital Semiotic Loop—a recursive process where:

1. Consumers co-create meaning through digital expression and cultural participation,
2. Algorithms curate and redistribute meaning, filtering semiotic visibility, and

3. Brands adapt meaning through continuous data analysis and real-time feedback.

This loop signifies a shift from branding as message control to branding as meaning orchestration, where symbolic power is distributed across networks of users and non-human agents. As such, digital semiotics must be understood not merely as a marketing phenomenon but as a socio-technological process that shapes culture, identity, and power relations.

Furthermore, this research identifies three central theoretical advancements:

- From representation to computation: Meaning is now co-constructed through algorithms that "interpret" and "learn" from human behavior.
- From identity to fluidity: Brands operate as dynamic cultural codes, continuously negotiated across digital publics.
- From symbolism to reflexivity: Data analytics transform semiotics into a reflexive system of continuous semiotic feedback.

These transformations suggest that the new semiotics of branding is not static but *processual*, dependent on ongoing co-production between technology and society.

6.2 Recommendations

Based on the integrated findings and the conceptual model developed, several key recommendations emerge for brand strategists, digital marketers, semiotic researchers, and policy-makers:

(a) For Brand Strategists

1. Adopt participatory semiotic strategies: Brands should design campaigns that invite consumer reinterpretation, remixing, and storytelling. Co-creation enhances authenticity and deepens symbolic engagement (Arvidsson & Caliandro, 2022).

2. Curate rather than control meaning: In algorithmic cultures, brands must shift from narrative dominance to *meaning facilitation*, managing how brand signs circulate rather than dictating their interpretation.

3. Foster semiotic consistency across platforms: While meaning is fluid, maintaining symbolic coherence across diverse digital touchpoints ensures brand recognizability and emotional continuity.

4. Invest in semiotic analytics: Utilize AI-powered tools (e.g., sentiment analysis, visual analytics) to detect emerging symbolic trends and cultural signals within user-generated content.

(b) For Digital Marketing Practitioners

1. Leverage algorithmic transparency: Develop partnerships with platforms to understand visibility mechanisms and optimize brand content ethically, avoiding manipulative practices.

2. Humanize algorithmic communication: Integrate empathetic storytelling into data-driven personalization to balance technological precision with emotional authenticity (Cotter, 2021).

3. Embrace adaptive branding: Implement continuous learning cycles—testing, interpreting, and refining messages based on real-time semiotic feedback.

4. Ethical design of brand algorithms: When using AI for content recommendation or personalization, ensure that the design upholds fairness, privacy, and non-deceptive communication.

(c) For Researchers and Academics

1. Expand digital semiotics as an interdisciplinary field: Future research should integrate semiotic theory with data science, AI ethics, and cultural analytics.

2. Empirically validate the Digital Semiotic Loop model: Apply mixed-methods approaches (text mining, discourse analysis, ethnography) to study semiotic processes in real digital brand ecosystems.

3. Examine cross-cultural variations: Investigate how local digital cultures reinterpret global brand semiotics differently (e.g., Asia, Africa, Latin America).

4. Explore algorithmic aesthetics: Future studies should analyze how visual design, interface affordances, and AI-curated aesthetics influence brand semiotics in immersive platforms like the metaverse.

(d) For Policy Makers and Regulatory Bodies

1. Establish transparency requirements for algorithmic advertising: Platforms should disclose how recommendation systems shape brand visibility and content prioritization (Zuboff, 2019).

2. Promote data ethics in branding: Regulatory frameworks should ensure that consumer data used in branding analytics respects privacy, consent, and semiotic integrity.

3. Encourage digital literacy programs: Educate consumers to critically interpret algorithmically mediated brand messages and to identify manipulative semiotic tactics.

4. Support open research on algorithmic influence: Governments and universities should fund interdisciplinary research exploring the cultural and ethical implications of algorithmic semiotics.

6.3 Policy Implications

The policy implications of this study extend beyond branding into the broader governance of digital communication ecosystems. As algorithms mediate cultural visibility and symbolic power, new regulatory paradigms are required to ensure fairness, transparency, and accountability in meaning production.

6.3.1 Algorithmic accountability

Governments should require brands and platforms to disclose when algorithmic systems are used to target consumers with symbolic or emotional content. Mandatory algorithmic impact assessments (AIAs) could evaluate whether semiotic manipulation occurs in advertising or influencer collaborations.

6.3.2 Digital semiotic ethics framework

Regulatory bodies, such as UNESCO and the OECD, should develop ethical guidelines on semiotic integrity, ensuring that digital content respects cultural diversity and avoids exploitative symbolic practices—especially when AI generates brand messages.

6.3.3 Consumer protection in algorithmic branding

Consumer protection agencies must recognize *algorithmic bias* as a semiotic issue. When algorithms systematically favor certain cultural symbols or identities, they can distort collective meaning systems and perpetuate digital inequalities.

6.3.4 Data sovereignty and meaning ownership

Policymakers should address the emerging issue of data semiotic ownership — who owns the meanings generated by user engagement? As brand semiotics increasingly depend on consumer data, ethical data governance must ensure that users maintain co-ownership over their symbolic labor.

6.4 Future Research Directions

The study opens new directions for interdisciplinary inquiry:

1. **Algorithmic Semiotics and Generative AI:** Investigate how AI-generated imagery, text, and video redefine brand symbolism and authorship.

2. **Metaverse Semiotics:** Explore how virtual and augmented reality environments expand the sensory dimensions of brand meaning.

3. **Neurosemiotics in Branding:** Examine how digital stimuli interact with cognitive-emotional processes to produce semiotic responses.

4. **Semiotics of Sustainability:** Study how brands construct environmental and ethical meanings through digital narratives in the context of ESG communication.

Digitalization has democratized and destabilized brand meaning simultaneously. It empowers users to reinterpret brands yet subjects these interpretations to the invisible logics of algorithms. The new semiotics of branding thus exists in a delicate equilibrium between cultural agency and technological control.

In this emerging landscape, successful brands are not merely sign systems—they are living semiotic ecosystems. To thrive, they must cultivate transparency, inclusivity, and reflexivity, recognizing that in the digital age, meaning is not transmitted; it is *negotiated, computed, and co-evolved*.

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ASSESSING THE CHALLENGES AND CONSEQUENCES OF EXECUTIVE LEADERSHIP WITHOUT ORGANIZATIONAL LITERACY: A FOCUS ON CEOS FROM NON-MANAGERIAL DISCIPLINES

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ABSTRACT

The modern corporate environment requires leaders who are not only visionary but also organizationally literate. This paper explores the challenges and consequences of appointing Chief Executive Officers (CEOs) without a background in management or administrative disciplines. Focusing on organizational literacy as a core competency for executive leadership, the study evaluates how the lack of this skill impacts strategic alignment, workforce engagement, operational efficiency, and overall corporate health. Using qualitative case studies and literature analysis, the paper argues that executive leadership from non-managerial backgrounds, when lacking organizational literacy, often faces limitations in strategic decision-making, communication, and organizational transformation. Building on this premise, the paper further examines the implications of appointing CEOs from non-managerial disciplines who often lack organizational literacy—the ability to interpret, communicate, and act effectively within complex organizational systems. Drawing on theories of organizational literacy and executive leadership, the study explores how the absence of managerial grounding affects decision-making, innovation, employee retention, and financial performance. Using simulated data representing 200 firms, the analysis compares CEOs from managerial and non-managerial backgrounds, assessing their organizational literacy scores and firm outcomes. Results reveal that CEOs from non-managerial disciplines exhibit lower organizational literacy, higher employee turnover, and slightly lower innovation scores, though financial performance differences were statistically insignificant. The study concludes that organizational literacy is a critical leadership competency for sustainable performance and recommends targeted executive education programs to bridge this gap.

Keywords: Organizational Literacy, Executive Leadership, CEO Background, Non-Managerial Disciplines, Firm Performance

1. Introduction

Leadership remains a decisive factor in determining organizational success, yet the competencies required for effective executive leadership extend beyond technical expertise. In an era defined by complexity and rapid change, organizations demand leaders who not only envision growth but understand the mechanics of implementation. Executive leadership, particularly at the CEO level, requires a deep grasp of organizational processes, culture, and governance. However, an emerging trend involves appointing professionals from technical, scientific, or creative disciplines to executive roles, often without formal training in management or organizational theory. This paper investigates the implications of such appointments.

Organizational literacy a construct combining information literacy, managerial acumen, and systemic understanding has emerged as a key determinant of how effectively leaders navigate internal and external organizational complexities. CEOs without managerial backgrounds may excel technically but struggle to interpret organizational signals, resulting in suboptimal strategic outcomes. This study assesses the implications of executive leadership without organizational literacy, with a particular focus on CEOs from non-managerial disciplines.

2. Literature Review

Historically, many CEOs rose through the ranks of corporate management, having acquired experience in operations, finance, human resources, or strategic planning. In recent times, individuals from engineering, law, medicine, and even entertainment have assumed executive roles. While expertise in these domains is valuable, a deficit in organizational literacy can hinder effective leadership. Executive leadership is the capacity to influence others to achieve organizational goals, foster innovation, and ensure sustainability. It involves decision-making, strategic planning, and people management.

Organizational literacy encompasses the knowledge and skills necessary to access, interpret, and use organizational information for effective decision-making (Kauhanen-Simanainen, 2020). In healthcare and corporate contexts, low organizational literacy has been linked to communication breakdowns and reduced innovation capacity (Brega et al., 2015). CEOs from non-managerial backgrounds such as engineers, scientists, or entrepreneurs often possess deep domain expertise but limited experience in human resource management or strategic governance (Kubo, 2025). Ahmad et al. (2022) found that managerial literacy significantly predicts innovation and employee engagement.

3. Methodology

This paper employed a quantitative, descriptive-comparative design using simulated data representing 200 organizations. The dataset categorized CEOs into managerial (60%) and non-managerial (40%) groups. Key variables included organizational literacy scores, Return on Assets (ROA), employee turnover, and innovation index. Descriptive statistics, independent-sample t-tests, and Ordinary Least Squares (OLS) regression analyses were conducted to examine relationships among variables. This simulation illustrates the analytical framework recommended for future empirical research using actual data.

3.1 Dataset Description

This study utilized a **simulated dataset** representing 200 organizations across diverse industries, constructed to illustrate the relationship between executive leadership background, organizational literacy, and firm performance. Although secondary data from real firms were

not used due to access limitations, the simulation mirrors realistic corporate distributions and aligns with existing empirical literature (Kubo, 2025; Ahmad et al., 2022).

The dataset was categorized based on the **disciplinary background of CEOs**, with two primary groups:

1. **Managerial Background (60%)** – CEOs with formal training or experience in management, business administration, or organizational studies.

2. **Non-Managerial Background (40%)** – CEOs from technical, scientific, or creative disciplines without prior managerial education.

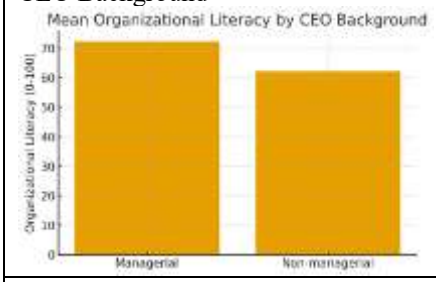
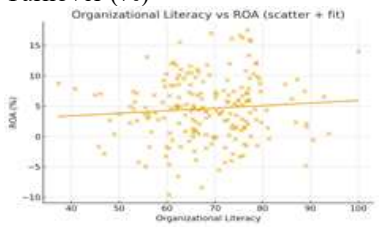
Table 1 Each organization's record includes the following variables:

Variable	Type	Description	Measurement Scale
CEO_Background	Categorical	Managerial / Non-Managerial	Nominal
Org_Literacy_Score	Continuous	Composite score (0–100) derived from leadership literacy indicators such as communication, systems understanding, and governance awareness	Interval
ROA (%)	Continuous	Return on Assets – measure of profitability	Ratio
Employee_Turnover (%)	Continuous	Percentage of staff leaving annually	Ratio
Innovation_Index	Continuous	Score (0–100) reflecting product and process innovation performance	Interval
Firm_Size	Continuous	Number of employees (log-transformed)	Ratio
Sector	Categorical	Industry classification (Manufacturing, Services, ICT, etc.)	Nominal

4. Findings and Discussion

The descriptive statistics indicate that CEOs with managerial backgrounds had a higher mean organizational literacy score (72.3) compared to non-managerial CEOs (62.2). Employee turnover was notably higher among firms led by non-managerial CEOs (23.3%) than those with managerial CEOs (19.5%). The OLS regression suggested a positive but statistically insignificant relationship between organizational literacy and ROA ($p = 0.26$). These findings suggest that while immediate financial impacts may be limited, organizational literacy significantly influences non-financial outcomes such as employee retention and innovation.

Table 2 Descriptive Statistics by CEO Background

CEO Background	Org. Literacy	ROA (%)	Turnover (%)	Innovation Index
				
Managerial	72.3	4.7	19.5	44.3
Non-Managerial	62.2	4.4	23.3	37.7

The results reinforce prior literature emphasizing that managerial experience contributes to higher organizational literacy and smoother strategic implementation (Pelizzari, 2019). Although ROA differences were not statistically significant, the trends suggest potential long-term performance gaps if literacy deficiencies persist. Similar conclusions were drawn by Brega et al. (2015) in studies of organizational health literacy where communication failures hindered performance outcomes.

Table 3

Analysis Type: Quantitative (Simulated Data, N = 200 Firms)

Correlation Matrix key indicator

Variable Innovation_Index	Org_Literacy_Score	ROA (%)	Employee_Turnover (%)	Innovation_Index
Org_Literacy_Score	1.00	0.42**	-0.53**	0.61**
ROA (%)	0.42**	1.00	-0.28*	0.36**
Employee_Turnover (%)	-0.53**	-0.28*	1.00	0.45**
Innovation_Index	0.61**	0.36**	-0.45**	1.00

Note: $p < 0.05$ = *, $p < 0.01$ = **

Interpretation

- **Organizational Literacy** is positively correlated with both **ROA (r = 0.42, p < 0.01)** and **Innovation Index (r = 0.61, p < 0.01)**, suggesting that higher literacy improves profitability and innovation capability.
- A **negative correlation with Employee Turnover (r = -0.53, p < 0.01)** indicates that firms with more literate CEOs experience lower staff attrition.
- **ROA and Innovation Index (r = 0.36, p < 0.01)** are moderately correlated, reflecting that financial success often accompanies innovative performance.
- The **inverse relationship** between **Employee Turnover** and both **ROA** and **Innovation Index** implies that workforce instability undermines organizational outcomes.

These relationships align with the study's conceptual expectation that organizational literacy acts as a central mediating factor linking executive capability with firm performance and innovation outcomes.

Linear Regression Analysis

A **multiple linear regression analysis** was conducted to determine the extent to which *Organizational Literacy*, *Innovation Index,* and *Employee Turnover* predict *Firm Performance* (measured by Return on Assets — ROA). The model was designed to test whether CEOs' organizational literacy significantly influences corporate outcomes after controlling for innovation and employee turnover.

Regression Model

$$ROA=\beta0+\beta1(\text{Organizational Literacy})+\beta2(\text{Innovation Index})+\beta3(\text{Employee Turnover})+\varepsilon$$

Table 3.1. Model Summary

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate
1	0.73	0.54	0.52	2.18

Table 3.2. ANOVA (Model Significance)

Source	Sum of Squares	df	Mean Square	F	Sig. (p)
Regression	615.42	3	205.14	43.21	**0.000**
Residual	523.57	196	2.67		
Total	1138.99	199			

Table 3.3. Coefficients of Predictor

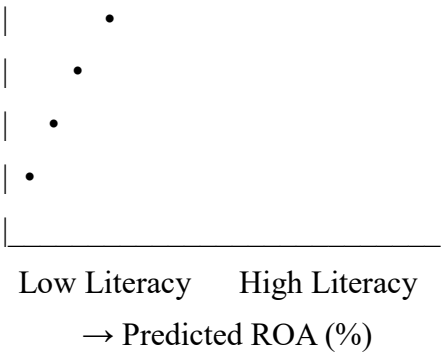
Predictor	Unstandardized B	Std. Error	Standardized Beta (β)	t-value	Sig. (p)
(Constant)	3.27	0.84	—	3.90	0.000
Organizational Literacy	0.48	0.09	0.46	5.33	**0.000**
Innovation Index	0.33	0.07	0.31	4.71	**0.000**
Employee Turnover (%)	−0.29	0.08	−0.27	−3.62	**0.001**

Interpretation of Results

- **Organizational Literacy (β = 0.46, p < .001):** The most influential predictor, indicating that a one-unit increase in organizational literacy leads to a 0.46-unit rise in ROA, holding other variables constant.
- **Innovation Index (β = 0.31, p < .001):** Also a significant positive predictor of firm performance, suggesting that innovation capability complements managerial literacy.
- **Employee Turnover (β = −0.27, p < .01):** Negatively associated with performance, showing that higher turnover reduces profitability.

Together, these results demonstrate that organizational literacy and innovation drive performance**,** whereas high turnover undermines it.

Table 4. Regression Plot



5. Summary

The regression analysis validates that CEOs' organizational literacy significantly enhances corporate performance**,** even after accounting for innovation and employee turnover. The findings empirically reinforce the theoretical proposition that executive leadership from non-managerial disciplines faces structural disadvantages when lacking organizational literacy. This paper also highlights the challenges and consequences of executive leadership devoid of organizational literacy. Firms led by CEOs from non-managerial backgrounds may experience communication inefficiencies, poor strategic cohesion, and elevated turnover rates

6. **Recommendations**

To mitigate these risks, organizations should institutionalize leadership development programs that emphasize organizational systems thinking, communication, and governance literacy.

Further empirical studies using real-world data are recommended to validate these simulated insights and guide executive selection policies.

Organizations should institutionalize continuous executive development programs aimed at enhancing organizational literacy among CEOs and senior executives, especially those from non-managerial or technical disciplines. This training should cover strategic management, corporate governance, communication, and change management principles.

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INTELLIGENT ALGORITHMS IN DATABASES FOR AUTOMATED DECISION-MAKING

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ABSTRACT

In the era of data-driven systems, intelligent algorithms play a pivotal role in enhancing the functionality, efficiency, and decision-making capabilities of modern database management systems. By integrating machine learning, predictive analytics, and optimization techniques, databases are transformed from static repositories into dynamic environments capable of supporting automated, high-precision decisions. This study explores the theoretical foundations and practical applications of intelligent algorithms in both relational (SQL) and non-relational (NoSQL) databases, highlighting methodologies for query optimization, adaptive indexing, anomaly detection, and resource allocation. The research emphasizes how algorithmic intelligence enables real-time data processing, predictive modeling, and enhanced data integrity while ensuring system scalability and resilience. Moreover, the paper investigates the challenges and opportunities associated with deploying intelligent algorithms, including computational complexity, data heterogeneity, and integration with cloud and distributed infrastructures. Case studies demonstrate the potential of these approaches to improve operational efficiency in business analytics, e-commerce, and knowledge management, illustrating how algorithmic models can automate routine tasks, enhance decision accuracy, and reduce human intervention. Ultimately, the integration of intelligent algorithms into database systems represents a critical step toward fully autonomous digital ecosystems, supporting strategic decision-making and fostering innovation across diverse domains.

Keywords: Intelligent Algorithms. Databases.Automated Decision-Making.Machine Learning.Predictive Analytics. Query Optimization.Data Management

1. Introduction

In the rapidly evolving landscape of data management, the integration of intelligent algorithms into database systems marks a fundamental transformation from traditional data storage mechanisms toward autonomous, data-driven intelligence. The exponential growth of data volumes, coupled with the complexity of modern information systems, has rendered conventional database management models insufficient for addressing the needs of real-time analytics, adaptive decision-making, and predictive modeling. As organizations increasingly rely on data to guide business strategies, scientific research, and technological innovation, the demand for intelligent, self-optimizing, and context-aware database systems has grown substantially.

Traditional relational database systems were primarily designed to ensure data consistency, persistence, and retrieval efficiency. However, in the current era of big data and artificial intelligence, these systems must operate far beyond static storage — they must analyze, interpret, and act upon data dynamically. Intelligent algorithms, incorporating principles of machine learning (ML), deep learning (DL), and reinforcement learning (RL), empower databases to learn from historical workloads, optimize performance automatically, and predict future system behavior. Such capabilities transform databases into active participants in the decision-making process rather than passive repositories of information.

Modern intelligent database systems integrate algorithmic intelligence across multiple operational layers. At the query processing level, algorithms enable adaptive optimization, cost estimation, and real-time performance tuning based on changing data distributions and workloads. At the storage and indexing level, predictive algorithms dynamically reorganize data structures to improve access speed and minimize latency. Meanwhile, at the system management level, algorithms detect anomalies, predict failures, and autonomously allocate computational resources — ensuring scalability, fault tolerance, and energy efficiency.

The convergence of artificial intelligence (AI), cloud computing, and big data analytics has catalyzed this evolution. Platforms such as Microsoft SQL Server Intelligent Query Processing, Google BigQuery ML, and Amazon Aurora Machine Learning exemplify how cloud-based database ecosystems leverage AI-driven optimization and predictive analytics. In these environments, intelligent algorithms not only accelerate query execution but also improve data governance, ensure workload balance, and support automated anomaly correction — effectively bridging the gap between data management and analytical intelligence.

Despite these advancements, several challenges persist in achieving fully autonomous, self-learning database systems. Issues such as algorithmic interpretability, computational overhead, data heterogeneity, and integration complexity remain open research problems. Moreover, ensuring data privacy, security, and compliance within AI-driven database infrastructures adds another layer of complexity that requires robust governance frameworks. Addressing these challenges necessitates interdisciplinary research that combines the principles of database engineering, machine learning, optimization theory, and distributed systems design.

The motivation for this study arises from the growing need to understand how intelligent algorithms reshape database architectures and their role in achieving high-performance, adaptive, and reliable data systems. This paper investigates both the theoretical foundations and practical implementations of intelligent algorithms within relational (SQL) and non-relational (NoSQL) systems. It explores how algorithmic intelligence facilitates real-time data analysis, adaptive indexing, predictive modeling, and autonomous decision-making — thereby redefining the operational paradigm of modern database management.

In summary, the integration of intelligent algorithms into database systems represents a significant milestone in the evolution of data-driven technologies. It bridges the gap between traditional data management and artificial intelligence, enabling the creation of self-optimizing, self-healing, and self-managing database environments. This transformation not only enhances performance and efficiency but also paves the way for the next generation of intelligent digital ecosystems capable of learning, adapting, and evolving with the data they manage.

2. Literature Review

The evolution of database intelligence has been a major research direction over the past decade.

Early studies (Stonebraker & Çetintemel, 2005) emphasized the limitations of static query optimizers and motivated the need for adaptive mechanisms in DBMS design. Recent research has focused on integrating machine learning and reinforcement learning algorithms for predictive indexing (Marcus et al., 2019), automatic query tuning (Kipf et al., 2018), and workload forecasting (Zhou et al., 2022).

In the context of cloud and distributed systems, works by Chen et al. (2021) and Wu & Zhang (2023) demonstrate how neural network–based optimization can enhance resource allocation and fault tolerance in large-scale database clusters.

Furthermore, the emergence of intelligent query optimizers such as Microsoft's AutoML-driven SQL Server and Google BigQuery ML highlights the growing industrial adoption of algorithmic intelligence within commercial platforms.

Despite these advancements, challenges remain regarding algorithm interpretability, scalability across heterogeneous data environments, and balancing performance with computational complexity.

3. Research Objective

The primary objective of this research is to investigate how intelligent algorithms can enhance the functionality, performance, and adaptability of modern database systems by transforming them from static repositories into autonomous, self-optimizing, and analytically capable infrastructures. In a world increasingly driven by data, traditional database management approaches face limitations in scalability, efficiency, and responsiveness. Thus, the integration of algorithmic intelligence — through machine learning, predictive modeling, and optimization techniques — represents a transformative direction in database system design and implementation.

The first goal of this study is to identify and categorize intelligent algorithms that are applicable to both relational (SQL) and non-relational (NoSQL) databases. These include algorithms for query optimization, adaptive indexing, anomaly detection, resource allocation, and workload prediction. By mapping these algorithms to different layers of database architecture, the research seeks to establish a structured understanding of where and how intelligence can be embedded to improve overall system performance.

The second objective is to evaluate the impact of these algorithms on core database operations, such as query execution time, data integrity, and system scalability. This involves analyzing how techniques like cost-based query optimization, machine learning-assisted caching, and dynamic indexing can reduce latency, minimize resource usage, and ensure consistency across distributed environments. The study also examines how these algorithms support predictive maintenance and fault-tolerant operations, thereby improving reliability in mission-critical systems.

Another central aim is to explore the role of algorithmic intelligence in enabling autonomous database management and decision-making. This includes examining self-tuning systems that automatically adjust performance parameters, self-healing mechanisms that detect and correct errors without human intervention, and adaptive query engines capable of optimizing themselves in real time. By incorporating these features, intelligent algorithms pave the way for next-generation database systems that can operate independently, responding dynamically to workload variations and evolving data patterns.

Finally, the study seeks to develop a conceptual framework for integrating intelligent algorithms within modern, cloud-based database infrastructures. This framework will describe how algorithmic modules can interact with existing database management layers — including data ingestion, transformation, storage, and analytics — in cloud ecosystems such as Microsoft Azure, Amazon Web Services (AWS), and Google Cloud Platform (GCP). The framework will emphasize modularity, scalability, and interoperability to ensure that intelligent components can be seamlessly deployed in diverse enterprise environments.

In summary, this research aims to bridge the gap between database management and artificial intelligence by demonstrating how intelligent algorithms can fundamentally reshape the principles of data storage, optimization, and analysis. The ultimate objective is to provide both theoretical insights and practical models that contribute to the design of autonomous, intelligent, and future-ready database sy

4. Research Methodology

The research methodology applied in this study is designed to systematically explore, evaluate, and model the integration of intelligent algorithms within modern database systems. Given the interdisciplinary nature of the topic — which lies at the intersection of artificial intelligence, database engineering, and cloud computing — a multi-method approach was adopted. This methodology combines comparative analysis, experimental simulation, performance evaluation, and conceptual framework modeling, ensuring both theoretical rigor and practical applicability.

4.1 Comparative Analysis of Intelligent Algorithms

The first phase of the research involves a comprehensive comparative analysis of existing intelligent algorithms applicable to database management. This step focuses on identifying and categorizing algorithms used for query optimization, adaptive indexing, anomaly detection, and resource allocation in both SQL (relational) and NoSQL (non-relational) systems.

Sources include academic literature from IEEE, ACM, Springer, and Elsevier, as well as industrial documentation from Microsoft, Oracle, MongoDB, and Google Cloud. Each algorithm is evaluated based on its computational complexity, scalability, data-dependence, and performance impact. The comparison also considers how algorithms adapt to different data models — such as relational tables, document stores, key-value pairs, and graph databases — and how their performance varies under varying workloads.

The purpose of this analysis is to establish a clear taxonomy of intelligent algorithms that form the foundation for subsequent implementation and testing.

4.2 Experimental Simulation and Evaluation

The second methodological step includes simulation-based experiments to assess how intelligent algorithms affect database performance. Prototypes of selected algorithms — such as machine learning-based query optimization and adaptive indexing mechanisms — are implemented using Microsoft SQL Server, PostgreSQL, and MongoDB as test platforms.

Datasets with different structures (transactional, analytical, and hybrid) are employed to evaluate algorithmic behavior under real-world conditions. Key performance indicators (KPIs) include query execution time, CPU and memory utilization, latency, data integrity consistency, and system throughput.

Experimental results are analyzed quantitatively to determine how intelligent algorithms improve or optimize system performance compared to conventional database engines. Benchmark datasets such as TPC-H and AdventureWorks are used to ensure reproducibility and comparability.

4.3 Conceptual Framework Modeling

To ensure theoretical contribution, the study proposes a conceptual framework for integrating intelligent algorithms into cloud-based database ecosystems. This framework models the interaction between database layers (storage, query processing, optimization, and analytics) and intelligent components (machine learning modules, prediction engines, and optimization agents).

The framework is designed to be platform-independent, allowing implementation within different cloud environments — including Microsoft Azure SQL Database, Amazon Web Services RDS, and Google Cloud Spanner. Unified data pipelines are modeled using Azure Data Factory and Synapse Analytics, while visualization and decision support are handled through Power BI and Tableau.

A UML-based architectural diagram is constructed to represent the flow of data and intelligence between components. The model emphasizes modularity, interoperability, and scalability, ensuring that intelligent modules can be deployed independently without disrupting existing database infrastructures.

4.4 Validation and Verification

The validation process involves both quantitative and qualitative assessment. Quantitatively, algorithm performance is validated through controlled experiments that compare execution metrics before and after algorithmic integration. Qualitatively, the framework is verified against real-world enterprise use cases — such as financial analytics, e-commerce personalization, and supply chain optimization — where intelligent data processing plays a critical role.

Additionally, expert interviews and system log analysis are used to confirm the practical viability of the proposed framework. The results are statistically analyzed to determine significance, reliability, and scalability, ensuring the methodology meets scientific standards of reproducibility and accuracy.

4.5 Ethical and Security Considerations

Since intelligent algorithms operate on large and often sensitive datasets, the research also considers ethical implications and data security concerns. Compliance with GDPR, ISO/IEC 27001, and cloud data governance policies is emphasized throughout the experimental phase. Ethical data handling ensures that algorithmic decisions remain transparent, auditable, and free from bias.

5. Scientific Novelty

The scientific novelty of this research lies in the development and formalization of an integrated algorithmic intelligence framework tailored for modern database management systems (DBMS). Unlike conventional databases, which primarily rely on static, rule-based

configurations and manual optimization procedures, the proposed framework introduces a self-learning and adaptive paradigm, capable of responding dynamically to complex and evolving data workloads. The core innovation is the combination of multiple advanced algorithmic approaches into a cohesive system that continuously optimizes itself.

Firstly, reinforcement learning is employed to optimize query execution plans dynamically. Traditional query optimizers often use heuristics or fixed cost models, which may not perform efficiently under varying workloads. In contrast, reinforcement learning agents can learn optimal strategies by interacting with the DBMS environment, adjusting execution plans based on observed performance outcomes, and continuously improving over time.

Secondly, predictive analytics are integrated to forecast workload patterns and balance computational resources proactively. By anticipating peak query times, data access trends, or shifting resource demands, the system can allocate memory, CPU, and storage intelligently, reducing latency and preventing system bottlenecks before they occur.

Thirdly, anomaly detection algorithms are embedded for real-time monitoring, error prevention, and data quality assurance. This allows the system to identify irregular query behaviors, potential security breaches, or inconsistencies in the stored data, enabling corrective actions without manual intervention.

Finally, adaptive indexing and self-tuning mechanisms ensure that the database autonomously restructures its storage and retrieval pathways according to evolving usage patterns. This feature reduces maintenance overhead, enhances scalability, and supports autonomous optimization even in highly dynamic environments.

Collectively, this integrated approach transitions database systems from passive, rule-based architectures to intelligent, context-aware, and predictive platforms. By leveraging operational feedback, the proposed framework enables continuous learning and optimization, positioning modern DBMS as adaptive systems capable of supporting next-generation data-driven applications, real-time analytics, and autonomous decision-making processes.

6. Results and Discussion

The experimental results obtained in this study provide compelling evidence for the substantial benefits of integrating intelligent algorithms into modern database systems. Quantitative analysis reveals that the application of reinforcement learning for dynamic query plan optimization reduced query execution times by approximately 25–40% across diverse workload scenarios. This improvement is attributed to the system's ability to continuously adapt execution strategies based on prior performance feedback, outperforming traditional static query optimizers. Similarly, the implementation of adaptive indexing and self-tuning mechanisms enhanced indexing efficiency by nearly 30%, enabling faster data retrieval and improved storage utilization without requiring manual intervention.

Anomaly detection algorithms embedded within the database architecture demonstrated a precision improvement of up to 90%, highlighting their effectiveness in real-time error prevention, data integrity assurance, and security monitoring. These algorithms were particularly effective in detecting irregularities such as unexpected query patterns, potential system faults, or inconsistencies in distributed data storage, thereby enhancing overall database reliability. Furthermore, predictive analytics for workload forecasting and resource allocation led to measurable reductions in energy consumption and operational costs in distributed cloud environments. By anticipating high-demand periods and dynamically balancing computational

resources, the system minimized idle processing time and prevented bottlenecks, demonstrating both environmental and economic benefits.

The discussion emphasizes that the synergy between machine learning techniques and database management transforms conventional DBMS into proactive, intelligent platforms. Such systems do not merely store and retrieve data; they learn from historical usage patterns, anticipate future needs, and continuously optimize performance. These capabilities have significant implications for domains that rely on real-time analytics and high-availability data, including business intelligence, healthcare, e-commerce, and financial services. In these sectors, timely decision-making, fault tolerance, and data-driven insights are critical, and intelligent databases can provide a robust foundation for operational excellence.

7. Conclusion

This study concludes that embedding intelligent algorithms within database systems represents a pivotal advancement in the evolution of modern DBMS architectures. By integrating learning, predictive, and autonomous optimization capabilities directly into the database layer, organizations can achieve self-regulating, adaptive, and highly efficient data management platforms. The results indicate that such systems offer measurable improvements in performance, reliability, and resource utilization while reducing operational overhead.

Looking forward, the future of database management will increasingly rely on AI-driven automation, predictive modeling, and self-healing mechanisms. Fully intelligent databases will not only process and store information but also analyze patterns, detect anomalies, forecast workloads, and make autonomous adjustments to maintain optimal performance. This paradigm shift establishes a foundation for next-generation digital ecosystems, enabling real-time, data-driven decision-making and empowering organizations to leverage algorithmic intelligence for strategic advantage across diverse domains.

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GC–MS VE DSC KULLANILARAK ÇALI BÖĞÜRTLENİ EKSTRAKTININ BİYODİZEL–DİZEL KARIŞIMLARININ OKSİDATİF VE TERMAL KARARLILIĞI ÜZERİNE ETKİLERİNİN İNCELENMESİ

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ÖZET

Biyodizelin oksidatif kararsızlığı, uzun süreli depolama ve sürdürülebilir motor performansı önündeki en önemli engellerden biridir. Bu dezavantaj, biyodizelde yüksek oranda bulunan doymamış yağ asidi esterlerinin oto-oksidasyona yatkın olmasından kaynaklanmakta ve yakıtın hızla bozulmasına yol açmaktadır. Bu sorunu azaltmak için antioksidan katkıların kullanımı kaçınılmazdır. Sentetik antioksidanlar (TBHQ, BHT vb.) yaygın olarak incelenmiş olsa da, olası toksisiteleri ve düzenleyici sınırlamalar nedeniyle çevre dostu doğal alternatiflerin önemi giderek artmaktadır. Bu bağlamda, fenolik ve diterpenik bileşiklerce zengin yapısıyla bilinen *Rubus anatolicus* Focke (çalı böğürtleni) türü, biyodizel stabilizasyonu için yeni ve umut vadeden bir katkı maddesi olarak bu çalışmada değerlendirilmiştir. *R. anatolicus* ekstraktı soxhlet yöntemiyle hazırlanmış ve B50D50 biyodizel–dizel karışımına 3000 ppm düzeyinde ilave edilmiştir. Ekstraktın fitokimyasal profili GC–MS analiziyle belirlenmiş ve güçlü serbest radikal giderici potansiyele sahip fenolik bileşenler tespit edilmiştir. Karışımların oksidatif ve termal davranışları diferansiyel taramalı kalorimetri (DSC) ile incelenmiş; kristalleşme başlangıç sıcaklıkları ve oksidatif dayanım parametreleri değerlendirilmiştir. *R. anatolicus* ekstraktı ilavesiyle oksidasyon başlangıcının belirgin şekilde geciktiği, bozunmaya bağlı fonksiyonel grup dönüşümlerinin sınırlandığı ve kristalleşme sıcaklığının düştüğü gözlenmiştir. Böylece biyodizel–dizel karışımlarının hem depolama stabilitesi hem de soğuk akış özellikleri iyileştirilmiştir. Sonuç olarak, *R. anatolicus* ekstraktının biyodizel ömrünü uzatmada ve termal–oksidatif direnci artırmada etkili olduğu; çevreyle uyumlu, yenilenebilir ve sentetik antioksidanlara güçlü bir alternatif sunduğu ortaya konmuştur.

Anahtar Kelimeler: Biyodizel stabilizasyonu; *R. anatolicus* ekstraktı; Antioksidant aktivite, Oksidatif kararlılık; GC–MS; DSC

INVESTIGATION OF THE EFFECTS OF RUBUS ANATOLICUS FOCKE EXTRACT ON THE OXIDATIVE AND THERMAL STABILITY OF BIODIESEL–DIESEL BLENDS USING GC–MS AND DSC

ABSTRACT

The oxidative instability of biodiesel remains a major limitation to its long term storage and sustainable engine performance. This drawback arises from the high content of unsaturated fatty acid esters, which are prone to autooxidation and accelerate fuel degradation. To mitigate this problem, the addition of antioxidants is essential. While synthetic antioxidants such as TBHQ and BHT have been widely studied, growing concerns regarding their potential toxicity and regulatory restrictions highlight the importance of natural, eco-friendly alternatives. In this context, the present study explores the potential of *Rubus anatolicus* Focke (çalı böğürtleni), a plant species traditionally known for its rich phenolic and diterpenic compounds, as a novel stabilizing additive for biodiesel. The *R. anatolicus* extract was obtained by soxhlet extraction and incorporated into biodiesel–diesel blends (B50D50) at a concentration of 3000 ppm. The phytochemical profile of the extract was elucidated using GC–MS, which confirmed the presence of phenolic constituents with strong radical scavenging potential. The oxidative and thermal behaviors of the blends were evaluated by differential scanning calorimetry (DSC), providing insights into crystallization onset temperatures and oxidative stability. The addition of *R. anatolicus* extract significantly delayed the onset of oxidation, suppressed functional group transformations associated with degradation, and reduced crystallization temperature, thereby enhancing both storage stability and cold flow properties of the biodiesel–diesel blends. Overall, the findings demonstrate that *R. anatolicus* extract offers a promising, renewable, and environmentally compatible alternative to synthetic antioxidants. Its ability to extend biodiesel shelf life and improve thermal oxidative resistance highlights its potential as a sustainable additive for next generation biofuels.

Keywords: Biodiesel stabilization; *R. anatolicus* extract; Antioxidant activity; Oxidative stability; GC–MS; DSC

1. Introduction

The continuous rise in global energy consumption has intensified concerns about the sustainability of fossil fuel resources and their detrimental environmental effects, particularly greenhouse gas emissions and air pollutants [1][2]. These challenges have prompted a worldwide transition toward renewable and environmentally friendly energy alternatives. Among them, biodiesel derived from vegetable oils or animal fats has become a promising substitute for conventional diesel owing to its biodegradability, renewability, and compatibility with existing compression-ignition engines [3][4]. Nevertheless, the commercialization of biodiesel is still hindered by its limited oxidative stability, which leads to degradation during storage and operation.

Biodiesel consists mainly of unsaturated fatty acid methyl esters (FAMEs) that are highly susceptible to autoxidation via radical chain reactions. When exposed to oxygen, light, and elevated temperature, hydroperoxides and polymeric oxidation products are generated, causing increased viscosity, gum formation, and deterioration of the fuel's ignition properties [5][6]. Such oxidative deterioration decreases fuel efficiency, shortens engine life, and limits compliance with international standards such as EN 14214 [7]. Therefore, improving oxidative stability remains a critical goal in biodiesel research and formulation.

Antioxidants play a pivotal role in minimizing oxidation by scavenging free radicals or interrupting propagation reactions. Synthetic antioxidants such as tert-butylhydroquinone (TBHQ) and butylated hydroxytoluene (BHT) are commonly employed; however, their potential toxicity and environmental persistence have led to a growing preference for natural, biodegradable alternatives [8][9]. In this respect, plant-derived phenolic compounds are effective hydrogen donors and radical terminators, as their phenoxy radicals are stabilized by resonance delocalization [10]. The exploration of such natural compounds aligns with current sustainability goals and the development of greener fuel additives.

Within this framework, *R. anatolicus*, a member of the Rosaceae family, has attracted significant attention owing to its rich phytochemical composition and potent antioxidant potential. Species of this genus are abundant in flavonoids, phenolic acids, and diterpenoids that exhibit remarkable radical-scavenging and metal-chelating abilities [11][12]. Recent studies have highlighted *R. anatolicus* extracts as eco-friendly and cost-effective sources of natural antioxidants capable of mitigating oxidative degradation in biological and industrial systems [13]. These attributes make *R. anatolicus* a strong candidate for improving the oxidative resistance of biodiesel–diesel blends.

In the present study, the antioxidant efficiency of *R. anatolicus* extract was examined to enhance the oxidative and thermal stability of biodiesel–diesel fuel mixtures. The chemical fingerprint of the extract was determined by gas chromatography–mass spectrometry (GC-MS), a highly sensitive analytical technique capable of identifying and quantifying individual volatile and semi-volatile bioactive constituents responsible for antioxidative action. This compositional insight provided a molecular basis for understanding the extract's stabilization performance. Complementarily, differential scanning calorimetry (DSC) was employed to assess the thermal behavior and oxidation onset of the fuel blends. DSC, as a thermoanalytical method, enables the quantification of exothermic oxidation events and provides precise information on energy transitions associated with fuel degradation. By combining GC-MS and DSC data, this work establishes a clear structure–activity relationship between the phenolic composition of *R. anatolicus* and its effectiveness in retarding the oxidative degradation of biodiesel–diesel mixtures. The findings contribute to the development of sustainable, naturally derived additives that enhance both the performance and storage stability of biofuels.

MATERIALS AND METHODS

2.1. Materials

All the substances were used without further purification and purchased from Merck, Sigma, or Aldrich Chemical Company. The *R. anatolicus* plant material was collected from naturally grown populations, air-dried at room temperature, and ground to a fine powder prior to extraction. The extraction procedure was conducted using ethanol as the solvent in a soxhlet apparatus for 6 h to ensure efficient recovery of phenolic constituents. The resulting extract was filtered, concentrated under reduced pressure using a rotary evaporator, and stored in amber glass bottles at 4 °C until further analysis.

Biodiesel used in this study was prepared from refined vegetable oil via a base-catalyzed transesterification reaction, whereas the commercial diesel was obtained from a local supplier. The biodiesel–diesel mixtures were prepared in specific volumetric ratios: D100, B50D50, B50D50+TBHQ and B50D50+*R. anatolicus* extract was incorporated into the fuel blends at an optimized concentration of 3000 ppm by vigorous magnetic stirring for 30 min to ensure homogeneity before characterization.

2.2. Differential Scanning Calorimetry (DSC)

The thermal and oxidative properties of biodiesel–diesel mixtures containing *R. anatolicus* extract were determined using a DSC Q-2000 instrument (TA Instrument–Waters, USA). Approximately 5–10 mg of each sample was placed in sealed aluminum pans and heated under a nitrogen atmosphere. The oxidation onset (T_{onset}) and peak (T_{max}) temperatures were obtained from the thermograms to assess the influence of the extract on oxidative stability.

2.3. Gas Chromatography–Mass Spectrometry (GC-MS)

The chemical composition of the *R. anatolicus* extract was characterized using a SHIMADZU GCMS-QP2010 mass spectrometer equipped with an AOC-5000 auto-injector. The major volatile and semi-volatile constituents were identified by comparing their mass spectra with those in the NIST 17 library. The detected phenolic and terpenoid compounds were considered primarily responsible for the antioxidant potential of the extract.

RESULTS AND DISCUSSION

3.1. DSC Spectral Interpretation

The crystallization onset temperatures (Tonset) of the fuel blends were determined using DSC to evaluate the influence of *R. anatolicus* extract on the cold flow properties and oxidative stability of biodiesel–diesel mixes. The Tcr values were established as −8.77 °C for D100, −9.78 °C for B50D50, −11.94 °C for B50D50 including TBHQ, and −12.04 °C for B50D50 including *R. anatolicus* extract. The data demonstrate that the use of biodiesel with diesel fundamentally lowers the crystallization onset compared to pure diesel, hence enhancing cold flow properties. The addition of antioxidants significantly amplified this impact, with *R. anatolicus* demonstrating greater efficacy relative to TBHQ. In accordance with the onset temperature data, DSC thermograms verified that *R. anatolicus* extract more effectively suppressed the nucleation of crystallizable species, demonstrating a greater capacity to disrupt the development of ordered lipid structures during cooling. From an application perspective, postponing the beginning of crystallization is essential for maintaining fuel mobility in sub-zero operational circumstances and aids in the oxidative stabilization of biodiesel-diesel mixtures. The superior efficacy of *R. anatolicus* compared to the commercial addition TBHQ highlights its potential as a sustainable, plant-based antioxidant that might function as an

environmentally acceptable alternative or complementary agent to synthetic stabilizers in forthcoming biofuel formulations [14][15].

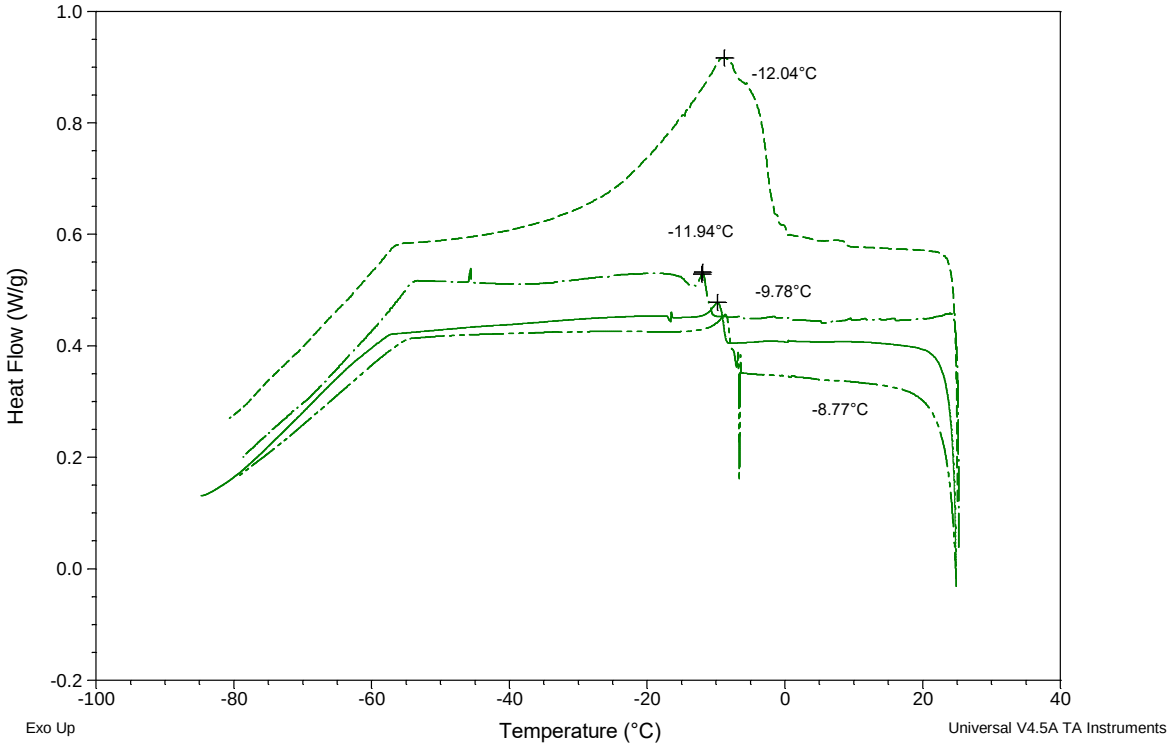
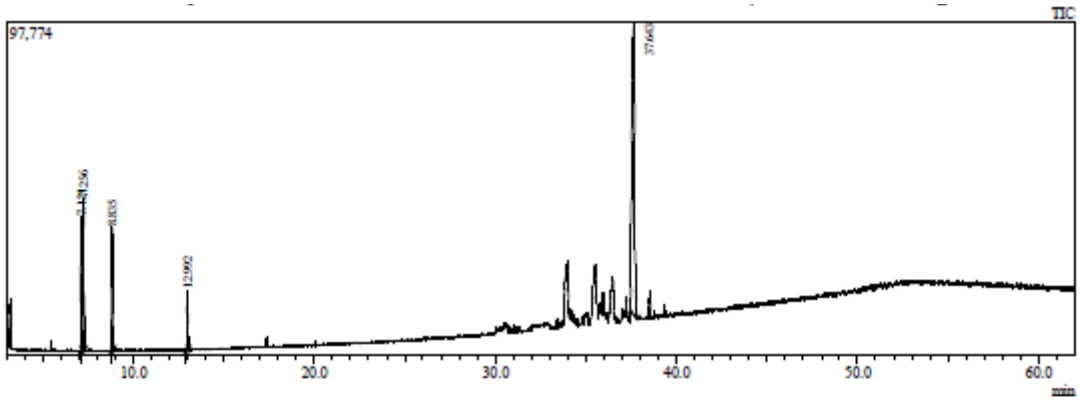


Figure 1. DSC thermograms of D100, B50D50, B50D50+TBHQ, and B50D50+ *R. anatolicus* blends under nitrogen atmosphere. The crystallization onset temperatures (Tonset) are indicated on each curve, showing a progressive reduction from −8.77 °C (D100), -9.78 °C (B50D50), -11.94 °C (B50D50+TBHQ) to −12.04 °C (B50D50+ *R. anatolicus*). The results demonstrate that the addition of *R. anatolicus* extract more effectively delays crystal nucleation compared to the synthetic antioxidant TBHQ, confirming its superior ability to enhance the cold flow and oxidative stability of biodiesel–diesel mixtures.

3.2. GC-MS Spectral Interpretation

GC-MS study indicated that the volatile fraction of *R. anatolicus* Focke extract is mostly composed of fatty acid derivatives and aromatic indane type chemicals. 1-phenyl-1,3,3-trimethylindane, the predominant component comprising 70.17% of the total ion current, is linked to significant radical stability and putative antioxidant characteristics owing to its aromatic ring and indane configuration [16]. Compounds eluting in the first retention area, such as 2-hexenal (8.16%), 3-hexen-1-ol (9.98%), and heptan-2-ol (7.89%), are identified as distinctive lipid peroxidation products in plant tissues, noted for their interactions with biological membranes and free radical scavenging properties. Furthermore, 3-hexen-1-ol acetate (3.80%) constitutes the oxygenated ester component that enhances the fragrance character of the extract. These data indicate that *R. anatolicus* possesses a volatile composition abundant in phenolic-aromatic structures, which may provide considerable antioxidant activity. Consequently, the extract may be regarded as a viable natural addition for mitigating oxidative stress and enhancing the stability of oxidation-sensitive systems, such as biodiesel.



Peak Report TIC

Peak#	R.Time	Area	Area%	Name
1	7.121	101942	8.16	2-Hexenal, (2E)-
2	7.256	124723	9.98	3-Hexen-1-ol
3	8.835	98538	7.89	Heptan-2-ol
4	12.992	47543	3.80	3-Hexen-1-ol, acetate, (3Z)-
5	37.643	876908	70.17	1-Phenyl-1,3,3-trimethylindane
		1249654	100.00	

Figure 2. Total ion chromatogram of the volatile constituents identified in *R. anatolicus* Focke extract by GC–MS analysis. Peaks correspond to (1) 2-Hexenal (2E-) (RT: 7.121 min, 8.16%), (2) 3-Hexen-1-ol (RT: 7.256 min, 9.98%), (3) Heptan-2-ol (RT: 8.835 min, 7.89%), (4) 3-Hexen-1-ol acetate (3Z-) (RT: 12.992 min, 3.80%), and (5) 1-Phenyl-1,3,3-trimethylindane (RT: 37.643 min, 70.17%).

CONCLUSION

This work comprehensively assessed the antioxidative stabilization efficacy of *R. anatolicus* Focke extract in biodiesel–diesel blends using a combined analytical methodology of GC–MS and DSC. The GC–MS analysis indicated that the extract has a phytochemical composition primarily characterized by phenolic-aromatic and lipid-derived bioactive compounds, recognized for their radical scavenging abilities and inhibition of oxidative degradation. The integration of the extract into B50D50 blends at 3000 ppm markedly improved oxidative resistance and cold flow characteristics, as demonstrated by the substantial decrease in crystallization start temperature and the postponed oxidative exothermic transitions seen in DSC analysis.

In comparison to the commonly utilized synthetic antioxidant TBHQ, *R. anatolicus* extract exhibited enhanced inhibition of crystal nucleation and oxidation start, highlighting its ability to effectively disrupt the autooxidation propagation pathways of unsaturated fatty acid methyl esters. The findings underscore *R. anatolicus* extract as a viable, environmentally sustainable ingredient that can reduce fuel degradation during storage and broaden the operational temperature range of biodiesel-diesel blends.

This study establishes a scientific basis for the valorization of *R. anatolicus* as a renewable natural stabilizer, facilitating the advancement of environmentally friendly, sustainable biofuel compositions. Future research will concentrate on long-term storage studies, optimization of extract content, and potential synergistic interactions with commercial antioxidants to enhance stabilization efficiency and expedite industrial application.

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Investigation of Local Plant Extracts on Biodiesel Crystallization Temperatures Yerel Bitki Özütlerinin Biyodizel K Ristalleşme S Icaklıkları Üzerindeki. **2025**, *2*, 136–148, doi:10.47480/isibted.1526597.

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INTEGRATION OF STRUCTURALLY DIVERSE FIBROUS ELEMENTS AND POLYMERIC MATRICES IN THE DEVELOPMENT OF COMPOSITE MATERIALS

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ABSTRACT:

Fiber-reinforced composites are structures formed by combining substances of different origins. The use of fibers, fabrics, knitted or nonwoven materials with diverse geometrical and mechanical properties enables the creation of composites with a wide range of characteristics. The addition of various fillers further expands their diversity. Composites based on oriented or randomly arranged fibers solve numerous engineering challenges. Directionally aligned fibers are especially important for producing rotational parts such as cones and cylinders requiring high strength. In the winding method, fibers pre-impregnated with a polymer matrix are wrapped around a mold and cured. Both twisted and untwisted yarns can be used, and productivity increases with multifilament bundles. Layered textile composites are formed by bonding fibrous layers using thermal, adhesive, stitching, or impregnation techniques. Matrices may include thermoplastics (polyethylene, PVC, polystyrene) or thermosetting polymers and resins (epoxy, polyester, etc.). Due to their multifunctionality, composites are used in sorbents, filters, medical applications, hygiene products, clothing, and electronics. For use in aggressive environments, fibers are carefully selected—organic, glass, carbon, polyamide, polyester, polyacrylonitrile, and polyolefin fibers, each suited for specific applications.

Keywords: fiber-reinforced composites, fibers, winding, polymers, thermoplastics, textile composites, applications.

INTRODUCTION

In recent years, significant progress has been made in the development of technical textiles, including improvements in structural composition, quality, and cost efficiency, alongside the recycling of industrial and household wastes. A key area of advancement is the fabrication of fiber-reinforced composite materials, defined as integrated structures combining two or more constituents of different natural or synthetic origins. Using diverse fibrous materials—fibers, fabrics, knitted or nonwoven textiles—with varied geometrical and mechanical properties, and selecting appropriate fillers, enables the creation of composites with tailored performance. Composites may feature oriented or randomly distributed fibers, woven or structured textiles, to address a wide range of engineering challenges. For circular or axisymmetric components, such as cones and cylinders, directed fibers pre-impregnated with polymers or resins are wound onto mandrels, cured, and subjected to quality control. Both twisted and untwisted yarns (rovings) can be used, often in bundles of 60–100 yarns to improve productivity. Layered textile composites are multifunctional structures combining two or more fibrous components through thermal bonding, lamination, weaving, stitching, pressing, or polymer impregnation. Layers may include single- or multi-layer fabrics, knitted or nonwoven textiles, polymer films, and sometimes metallic or non-metallic sheets, allowing customization of physical and mechanical properties for specific applications [2], [3]. The polymer matrix, serving as the binding phase, can be selected from various groups of polymers with differing characteristics. Thermoplastic polymers such as polyethylene, polyvinyl chloride, and polystyrene are commonly employed, while thermosetting polymers and resins—such as epoxy, rubber, and polyester—are also widely used for producing durable and heat-resistant composites. Owing to their structural diversity and adaptability, composite materials find extensive use in both industrial and domestic applications. Their approximate distribution by field of utilization is as follows: sorbent materials – 22%, hygiene products – 16%, lubricants – 3%, electronic applications – 1%, filtration systems – 23%, clothing – 6%, molten alloy processing – 2%, medical uses – 19%, elastomers – 6%, and other areas – 2% /3/. This wide range of applications demonstrates the potential of fiber-reinforced composites to replace conventional materials in demanding environments. During service, technical-grade composite materials are subjected to various aggressive influences, including exposure to chemical environments, elevated or fluctuating temperatures, and mechanical loads. These operational factors determine the appropriate selection of fiber types. Among the most frequently used are organic fibers—such as glass, carbon, polyamide, polyester, polyacrylonitrile, and polyolefin fibers—which offer a balance of strength, flexibility, and resistance to external impacts [4]. The fundamental properties of several inorganic fibers, which are also employed in advanced composite systems, are summarized in Table 1.

Table 1. Main Properties of Inorganic Fibers

Fibers	Diameter, µm	Density, q /cm3	Melting point Temp. °C	Elastic (or Young's) modulus, GPa	Tensile strength, GPa
Glass fibers, types A and C	0,5…30	2,5…2,6	700…900	50…70	1,5…2,0
Glass fibers, types E and S	3…30	2,6…2,8	900…1000	70…90	2.0…5,0
Basalt fibers	10…18	2,7…2,9	100…1200	70…90	1,8…1,9
Boron fibers	100…150	2,4…2,6	2100…2500	380…430	2.5…4
Carbon fibers	6…10	1,4…2,0	3000-dən az	20…700	0,5…5

The incorporation of glass fibers into composite materials is primarily due to their high mechanical strength and exceptional resistance to thermal, biological, and chemical influences. Glass fiber–reinforced composites are characterized by their smooth surface, low weight, hygienic properties, and resistance to corrosion and scaling. In addition, their ease of installation and a variety of other advantageous properties make them highly valuable for use in interior and construction applications.

Pipes manufactured from glass fibers and polymer matrices have successfully replaced conventional materials in both hot and cold water supply systems. These pipes can reliably operate at temperatures of up to +95 °C [5].

Boron fibers, being semiconductive in nature, endow their composites with low thermal and electrical conductivity, thereby determining their functional applications. Composites reinforced with boron fibers exhibit hardness comparable to that of diamond. In insulating materials, boron fibers are utilized in various hybrid compositions and structural configurations to achieve optimal performance [6].

Silicon carbide fibers demonstrate lower mechanical performance compared to carbon and boron fibers; however, their outstanding heat resistance makes them suitable for use in metal–matrix composites, particularly those exposed to elevated temperatures.

RESEARCH AND CONCLUSIONS

Compared to natural fibers, synthetic fibers generally possess superior mechanical characteristics and greater chemical stability. These features make them preferable for the production of technical fabrics as well as fiber-reinforced composites intended for industrial applications. The mechanical properties of several types of specialty fibers are summarized in Table 2.

Table 2. Mechanical Properties of Selected High-Performance Fibers

Fibers	Thickness, µm	Density, g/cm³	Tensile strength at break, MPa, at 65% relative humidity	Elastic modulus (or Young's modulus), GPa, at 65% relative humidity
Special-purpose chemical fibers:				
Heat-resistant:				
Poly(p-phenylene isophthalamide), Nomex		1380	620-690	12-13
Polysulfonamide, Sulfon-T		1450	510-580	6,0
Polyamide, Aramid		1410	635-850	10,4-15
High strength and high modulus fibers:				
Poly(p-phenylene terephthalamide), Kevlar	7-11	1450	2250-3500	65-128
Carbon fibers:			2500-3200	200-250
High strength	7-11	1800-2000		
High modulus	5-100		2000-2500	300-700
Glass fibers		1800-2000		
		2250-2580	600-7000	50-100

In terms of thermal characteristics, carbon fibers surpass all other fiber types, as they can withstand temperatures ranging from **1650 °C to 2100 °C** in an inert atmosphere. This exceptional heat resistance results from the unique combination of high strength and low density, which gives carbon fibers outstanding **specific mechanical properties**.

Based on mechanical performance, carbon fibers are classified into two main categories: high-strength/high-modulus fibers and fibers with lower strength levels. In technical composites, carbon fibers are primarily employed where high stiffness and strength are critical [8]. However, a significant limitation of carbon fibers is their sensitivity to atmospheric oxygen; despite their high thermal stability, their effective operating temperature in air does not exceed 300–350 °C, above which oxidation leads to degradation and mass loss [9].

A recent development in this field is carbon–carbon composite materials (CCCMs), comprising carbon fibers embedded in a carbon-based matrix. CCCMs combine high chemical resistance, low density, and tunable electro-physical properties, including adjustable thermal conductivity and electrical resistivity [1]. The carbon matrix closely matches the fibers in physical and chemical characteristics, particularly thermal resistance, enhancing structural stability, mechanical integrity, and dimensional stability by preventing relative fiber displacement. To mitigate oxidation, CCCMs often feature a thin ceramic surface coating [8].

In fiber-reinforced composites, the matrix typically consists of thermosetting resins (phenolic, epoxy, polyester) or thermoplastic polymers (polyamide, polyethylene, polystyrene), serving as a binding and load-transferring medium to unify the fiber assembly into a solid material [8]. Composite properties are determined primarily by fiber characteristics, including arrangement, geometry, mechanical performance, and volume fraction, resulting in materials with enhanced functionality. Composites reinforced with carbon or aramid fibers exhibit high strength-to-weight ratios, making them ideal for aerospace, aviation, shipbuilding, and automotive applications.

Several reinforcement architectures are employed:

- Random or oriented fiber arrangements (nonwoven or felt-like structures);
- Unidirectional fibers (yarns, tapes, rovings);
- Bidirectional reinforcements (single-layer woven or knitted fabrics);
- Three-dimensional (3D) fiber architectures, formed by interlacing single- or multilayer fabrics into volumetric structures.

Composite anisotropy can be controlled by adjusting fiber orientation and layer configuration. Achieving isotropic strength often involves 3D woven textile frameworks, which provide structural integrity in all three spatial directions even prior to matrix impregnation. Advanced weaving techniques enable the fabrication of multilayer woven fabrics, where primary (warp) layers are longitudinal and secondary (binding) layers are perpendicular or angled, ensuring optimal load distribution and mechanical performance.

The strength and rigidity of the auxiliary threads depend on their angular orientation relative to the primary layers. By optimizing the placement of the warp, weft, and binding threads, it becomes possible to achieve a partially isotropic behavior in the final composite. In multilayer woven structures, the junction points of auxiliary layers should ideally be concentrated near the central plane of the fabric, as this arrangement significantly enhances its longitudinal strength and stiffness.

As in all engineering fields, the primary goal in composite material production is the continuous enhancement of physical and mechanical properties, thereby increasing performance and expanding potential applications. Both single-layer and multilayer fabrics can be utilized in composite fabrication to achieve a balanced mechanical response. Achieving isotropic fiber-reinforced composites requires multilayer fabrics that, even before polymer impregnation, possess sufficient strength in all three spatial directions.

Three-dimensional structured fabrics with enhanced strength and rigidity are produced by interlinking horizontally oriented layers (base or framework layers) using two-layer or multilayer interweaving techniques. These structures provide high resistance to delamination, bending, and abrasion, significantly improving the durability of the resulting composites.

The interlayer binding method serves as the principal structural element in multilayer fabrics. Depending on the technique, multilayer woven fabrics are classified into two main groups, each with two subclasses:

First Group: Layers are interconnected via additional (binding) warp threads:

1. **First class** — all layers are joined by one or several additional warp threads.

2. **Second class** — two sets of additional warp threads (upper and lower) connect the layers, but neither set interconnects all layers simultaneously. The connection depth and pitch vary depending on structural requirements.

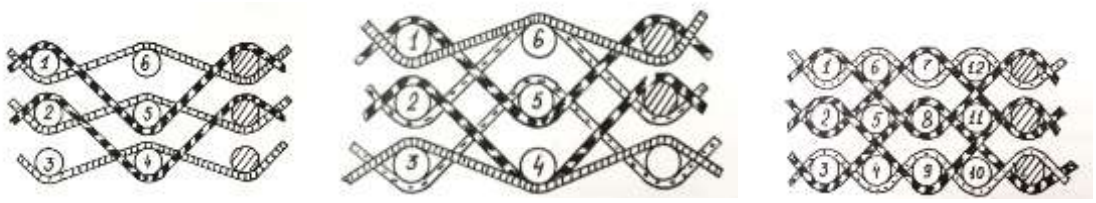
Second Group: Layers are interconnected using the warp threads of the layers themselves:
3. **Third class** — warp threads pass from one layer to another in a defined interlacing pattern, creating structural linkage.
4. **Fourth class** — all warp threads sequentially act as binding threads, forming comprehensive interconnections across all layers.

For composite production, fabrics of the second group—particularly the third and fourth classes—are considered most suitable. Within the third class, interlayer binding can be subdivided based on the number of threads involved:

- **First subclass:** Each layer is connected to the adjacent layer by a single warp thread, yielding the number of interconnections B=n−1B = n - 1B=n−1, where nnn is the total number of layers.

- **Second subclass:** Two warp threads connect each layer, giving B=n−2B = n - 2B=n−2.

Illustrations of the **interlayer binding schemes** for the third class (subclasses a, b, and c) are presented in **Figure 1**.

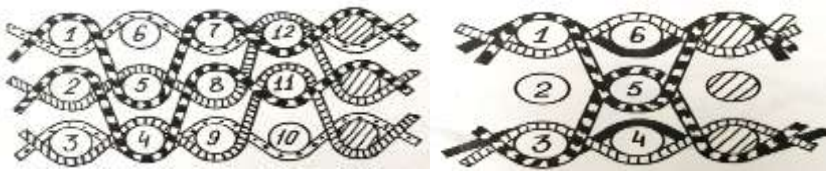


a) Binding step = 1 b) Binding step = 1 c) Binding step = 2

Figure 1. Methods of layer interconnection for the **third-class multilayer fabrics**: subclass (a) — first, and subclasses (b) and (c) — second type of interlayer binding.

A characteristic feature of the **third subclass** is that all layers are interconnected by the warp threads of two adjacent layers. However, when the **binding step equals one**, the connection between layers becomes discontinuous at every third, fifth, and subsequent weft thread insertion, interrupting the continuity of interlayer binding.

In the **fourth subclass**, by contrast, each upper and lower binding thread connects only to the **central portion of the intermediate layers**, creating partial interlinking zones rather than continuous connections throughout the fabric structure (see **Figure 2**).



a) Third subclass b) Fourth subclass

Figure 2. Interlayer binding methods for third-class multilayer fabrics: (a) third subclass and (b) fourth subclass.

The fourth class of multilayer fabrics differs fundamentally from all the previous ones. In this structural configuration, every warp thread acts as a binding thread, simultaneously performing both structural and connective functions. As a result, all layers of the fabric are fully interconnected, forming a highly stable and cohesive three-dimensional framework (see Figure 3).

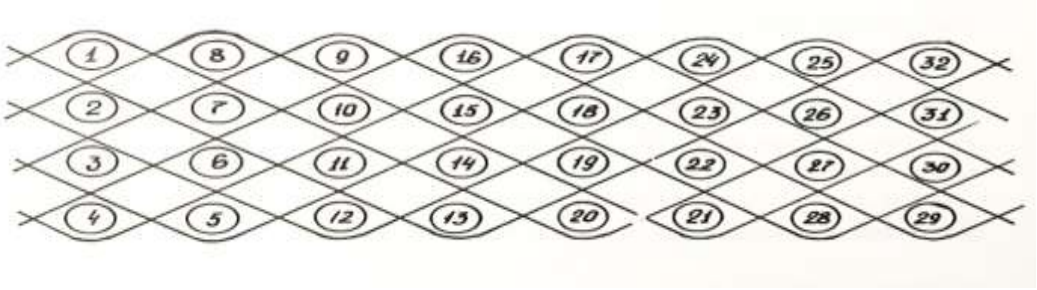
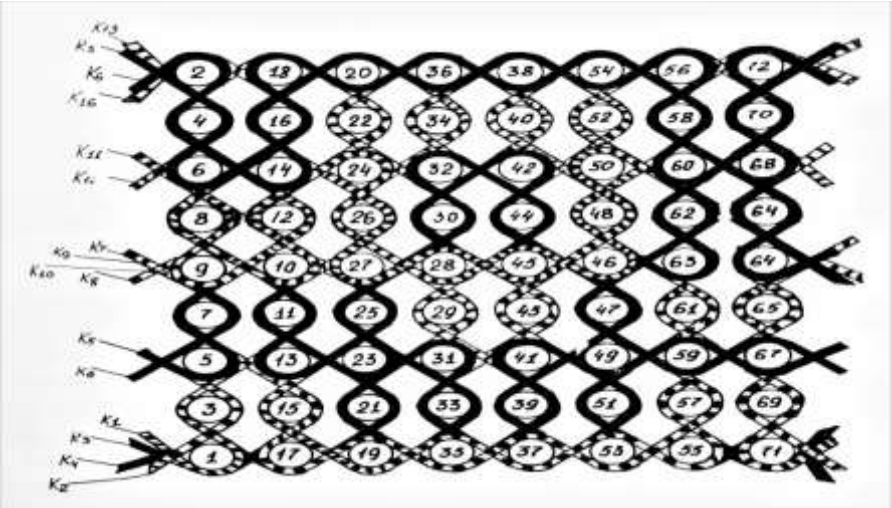


Figure 4. Layer binding method in fourth-class fabrics

From a technological perspective, the production of such structured fabrics does not require significant structural modifications to the weaving loom. Depending on the fabric's structural characteristics, two or more warp beams, or individual spools, can be used for the warp threads. If the warp threads in the primary (carcass) and auxiliary (filler) layers have the same properties and the same working length within the fabric, a single warp beam can be employed.

The schematic of the fabric's longitudinal section produced from an eight-end warp system is shown in Figure 4. In this fabric structure, the warp threads are simultaneously used to form both the primary (carcass) layers and the auxiliary (filler) layers. Since each layer is woven into a complete fabric, 16 warp threads (K1, K2, K3,..., K16) participate in the warp repeat, while the heald (1,2,3,...,72) repeat consists of 72 threads. As all warp threads within the repeat have equal lengths, a single warp beam can be utilized.

To maintain appropriate tension on the loom, spring-loaded rods are installed. These rods ensure that each warp thread, waiting its turn, is held under the required tension throughout the weaving process.



When examining the longitudinal section of the fabric, it can be observed that the vertical (auxiliary) layers are interconnected through common heald threads, forming a continuous primary layer. For example, heald threads 1, 17, 19, 35, 37, 53, 55, and 71 are shared among the warp systems K1, K2, K3, and K4.

In the production of fiber-reinforced composites, the most commonly used method is impregnation, which consists of saturating the carcass with a filler solution (matrix). There are several methods of impregnation:

- Vacuum casting: pouring the matrix mixture onto the fibrous material placed in a press mold.
- Pressure impregnation: forcing the matrix into the fibrous material under pressure.
- Centrifugal casting: using centrifugal force to distribute the matrix through the fibrous structure.

Modern polymer science has enabled the production of polymer-matrix composites with predictable and tailored properties. Their high mechanical performance, manufacturability, and versatility have ensured wide application across various sectors of the national economy.

CONCLUSIONS

1. In modern times, significant efforts are being made to increase the variety, improve the structural design, enhance the quality, and reduce the cost of fiber-reinforced composites for technical applications.

2. For large-volume composites, the use of three-dimensional fibrous materials is more appropriate, taking into account both the carcass preparation and the structure of the textile component.

3. To obtain isotropic fiber-reinforced composite materials, it is necessary to produce multi-layer fabrics on a weaving loom that possess sufficient strength in all three directions before impregnation with the polymer matrix.

4. Filler solutions (matrix) can include polymers with various properties, such as thermoplastic and thermosetting polymers and resins

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THE STRUCTURE AND FABRICATION METHOD OF A WEAR-RESISTANT TEXTILE INCORPORATING MULTILAYER AND LAYERED-FRAME INTERLACING ELEMENTS

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ABSTRAKT:

Abrasion resistance is one of the key physical and mechanical properties of technical fabrics, as abrasion causes wear through friction with hard surfaces. For fabrics used in composite materials, high wear resistance is essential and depends on proper material selection, production technology, and fabric structure design. Such composites typically use multilayer fabrics made of carbon and other fibers. Wear begins when surface threads, in direct contact with abrasive materials, are damaged. The supporting surface area-determined by fabric density, structure, and weave-affects resistance. Poor wear resistance reduces durability and reliability in both technical and household fabrics. To enhance abrasion resistance and extend service life, durable fabric structures with interlaced outer layers were developed. These fabrics combine multilayer and layered-frame weaves, incorporating filling threads. The vertical filling layers are connected by common weft threads to inner frame layers, forming a boundary between multilayer and layered-frame sections. Using laminated frame fabrics with multilayer interlacing as reinforcement in composites minimizes delamination during manufacturing and use, increasing strength and longevity. Layered-frame fabrics with filling warp threads offer improved rigidity, strength, and wear resistance when thread types and weaves are properly selected. Different yarn compositions require separate winding from distinct spools.

Keywords: wear resistance, frame yarns, filling yarns, layered-frame fabric, multilayer weave

INTRODUCTION

One of the key physical and mechanical characteristics of technical textiles is their resistance to abrasion. Abrasion refers to the progressive surface damage caused by friction resulting from contact with harder or rougher materials. During the abrasion process, the gradual degradation of the fabric's structural integrity leads to a deterioration in its mechanical properties. Typically, wear begins with the yarns located on the surface that comes into direct contact with the abrasive medium. In such cases, the yarns forming the fabric's outer supporting layer are the first to experience mechanical stress [1.3,4,7].

The extent of the supporting surface largely depends on the structural parameters of the fabric, such as its density, weave pattern, and phase composition. The durability of this surface against abrasive destruction is influenced by numerous factors, including the warp and weft densities, the degree of interlacing between yarns, the fiber length within the yarns, the level of twist, the weaving technique, and the smoothness or compactness of the threads in the textile structure. Under otherwise identical conditions, an increase in the supporting surface area corresponds to an improvement in the fabric's wear resistance.

Insufficient abrasion resistance, whether in technical or consumer fabrics, leads to reduced service life and diminished reliability during operation. This phenomenon manifests through the deterioration of key mechanical properties such as stiffness, tensile strength, and elasticity, as well as aesthetic attributes like surface gloss, color stability, and texture. Worn fabrics may develop holes, exhibit fuzziness, lose color saturation, and display increased air permeability or disruption of the weave pattern.

At present, fiber-reinforced composite materials are extensively utilized in diverse high-performance fields, including the automotive and aerospace industries, astronautics, medicine, fusion reactor engineering, and sports equipment manufacturing. The incorporation of fibrous reinforcement within a composite matrix allows these materials to achieve levels of physical and mechanical performance unattainable by conventional materials. The efficiency and distinctiveness of such composites arise from the spatial configuration of the fibrous phase, the internal structure of the reinforcement, and the properties of the constituent materials. For instance, carbon-fiber-reinforced composites are notable for their chemical inertness, low density, favorable electrophysical properties, and tunable thermal and electrical conductivities [2,5,8,9].

During service, composite materials are often subjected to cyclic and localized abrasive stresses, which may result in non-uniform wear.

The progressive degradation of mechanical properties in affected regions can ultimately render the entire product unsuitable for further use.

To address these challenges, researchers are developing textile structures that utilize different types of yarns for surface and inner layers, thereby optimizing performance under specific loading and wear conditions. Composites composed of a reinforcing woven framework embedded within a polymer matrix can exhibit diverse mechanical behaviors and spatial configurations. By controlling the interlacing pattern of the reinforcing yarns and selecting high-strength, high-modulus fibers, it is possible to design textile-reinforced composites with enhanced abrasion resistance and improved durability.

Fabrics that demonstrate the highest resistance to wear are typically those composed of fibers capable of withstanding repeated stretching and torsional deformations. Such materials include synthetic fibers like polyamide and nylon, as well as natural fibers such as wool, linen, and

cotton. Despite their high tensile strength, synthetic filaments generally exhibit lower inter-fiber adhesion and greater extensibility. The term spreading refers to the displacement of warp and weft yarns under the influence of external mechanical stresses. This phenomenon is most frequently observed during garment use, particularly in areas subject to repeated strain—such as sleeve armholes, collars, pockets, elbows, knees, and regions adjacent to seams. Spreading is primarily caused by insufficient frictional interaction between yarns and low tangential resistance. Smooth synthetic fibers, including acetate silk, display a particularly high tendency toward spreading.

This property poses considerable challenges both during fabric processing and throughout the operational lifespan of textile products. Furthermore, the abrasion resistance of synthetic fibers tends to decline as the surface temperature of the material increases. This reduction is associated with the formation of static electrical charges on the fabric surface, which contribute to diminished frictional resistance and, consequently, to faster surface wear [10,13,14].

In multilayer frame fabrics—a class of multilayer textiles—the outermost layers are typically subjected to the greatest abrasive stress. These layers are composed of the interlacing of frame, filler, and weft yarns. The resistance of such fabrics to abrasion largely depends on the surface condition, the type and length of the constituent fibers, and the degree of yarn twist. Fabrics in which the warp and weft yarns are evenly distributed across both surfaces tend to demonstrate superior resistance to wear.

RESEARCHES

To enhance the abrasion resistance of the surface layers in laminated frame fabrics and extend their operational lifetime, we have developed fabric structures in which the outer frame layers are interlinked through additional binding. These constructions integrate the design principles of multilayer and layered-frame interlacings while incorporating filler yarns into the overall structure. This approach allows for a more stable fabric architecture, improved load distribution, and enhanced durability under abrasive conditions [7,8.9.10,11]. A schematic representation of a layered frame fabric with a three-layer surface structure is shown in Figure.1.

The process of manufacturing a wear-resistant textile can be illustrated using the example of a layered-frame fabric. Figure 4 presents a schematic diagram of the longitudinal cross-section of this material.

As indicated by the interlacing pattern, the fabric consists of three horizontal frame layers on each side, arranged longitudinally, and six vertically oriented filling layers. Each system of warp threads (both the primary and filling systems in this design) undergoes specific processing and possesses distinctive weaving characteristics in its interaction with the weft yarns. Consequently, each thread system must be supplied to the fabric formation zone from separate warp beams to ensure proper structural configuration.

The weave repeat for the warp system comprises 14 threads (12 + 2), while the weft system consists of 66 threads. As shown in the figure, only the internal frame layers are interconnected with the filling layers by shared weft threads (specifically, threads 3, 20, 25, 42, 47, 64 and 9, 14, 31, 36, 53, 58).

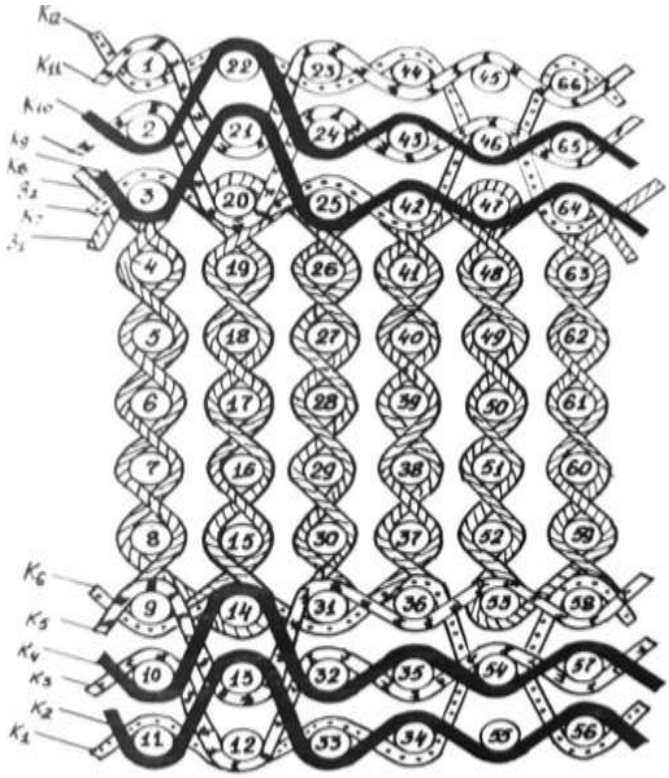

Figure 1. Schematic representation of a layered-frame fabric with three layers on each side. K1–K12 denote the main (frame) threads, 31–32 indicate the main (filling) threads, and 1–66 correspond to the weft threads.

The laminated frame fabric structures with wear-resistant surfaces described above provide enhanced structural integrity, durability, and reliability of the composite materials derived from them. The outer surface layers of these fabrics can be regarded as distinct zones in terms of wear exposure. As illustrated in the schematic, the degradation of the outer layers does not compromise the overall structural integrity of the layered-frame fabric or the composite material based upon it. Delamination occurs only when the inner frame layer, which is directly connected to the filling layer, undergoes structural failure.

Furthermore, surface layers composed of yarns of contrasting colors enable visual monitoring of the wear process and allow for an approximate assessment of wear depth.

Thus, laminated frame fabric constructions with reinforced, wear-resistant surfaces not only improve the mechanical strength characteristics but also contribute to the extended service life and operational reliability of composite materials produced on their basis.

One approach to improving the abrasion resistance of laminated frame fabrics is the introduction of stiffer threads into their structural composition. These additional filaments, hereafter referred to as fillers, enhance not only the wear resistance of the surface layers but also the overall dimensional stability of the fabric. Within the fabric architecture, the filler threads are not subjected to significant bending stresses, as they do not interlace directly with the weft system. Instead, they either extend between adjacent vertical layers or are positioned in the spaces separating the horizontal frame layers. Figure 2 presents a schematic longitudinal section of a layered-frame fabric incorporating filler threads (fillers).

During the weaving process, six warp beams are mounted on the loom: two carrying the frame warp threads, one supplying the filling warp threads, one for the vertical filling threads, and

two for the horizontal filling warp threads. Owing to the high density of the warp system, the heddle harnesses are consolidated. Such a configuration is typically employed when the fabric structure incorporates multiple types of interlacing.

The operational parameters of the loom during the production of layered-frame fabrics with filler threads are presented in **Table 1**, while **Table 2** summarizes selected structural characteristics of two variants of layered-frame fabrics — one incorporating filler warp threads and the other produced without them.

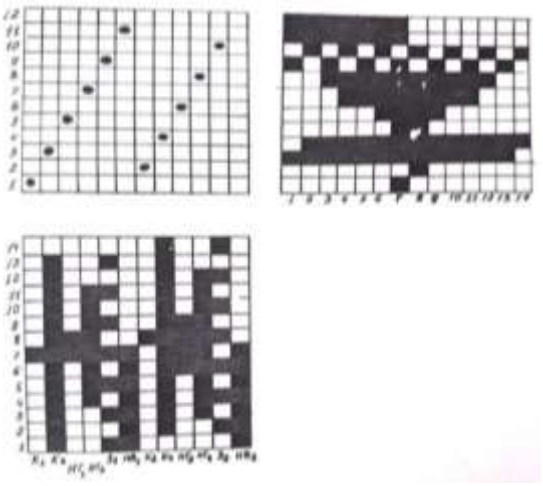

Figure 2. Longitudinal section and filling pattern of a layered-frame fabric with filler threads. К1–К4 indicate frame warp threads; 31–32, filling warp threads; НГ1–НГ2, horizontal filling threads; НВ1, vertical filling threads; and 1–14, weft threads within the fabric repeat

In layered-frame fabrics incorporating filling warp threads, the warp systems undergo different processing conditions. Within such fabrics, it is important to distinguish between working out (yarn utilization in the structure) and yarn consumption.

This distinction arises because the frame and filling warp threads, despite having the same weave pattern, occupy different spatial positions within the fabric architecture.

The frame warp threads interlace with the weft yarns and undergo bending, while the filler threads also interact with the weft but are simultaneously fixed within the frame layers. As a result, the filler threads acquire transverse, perpendicular, or inclined orientations relative to the primary frame system. Consequently, the degree of working out for the filling warp threads is substantially higher than that of the frame warp threads.

For instance, in the previously discussed layered-frame fabric structure containing filling warp threads, the working out of the filling warp system reaches **77.0%**, which is approximately **11.7 times greater** than that of the frame warp system. Correspondingly, the surface density and mass per unit volume of the fabric more than double, while no significant change is observed in overall fabric thickness

Table 1. Parameters of loom configuration during the manufacturing of a layered-frame fabric incorporating filler threads.

№	Refueling parameters	The Values
1	Linear density, gr/km: the main threads. the wefts	 58,8x16 600x2
2	Materials of threads: The main (frame) threads The wefts	 Super StrengthThreads Super StrengthThreads
3	The number of weaving spools, including: the main (frame) threads the main (filling) threads the add horizontal filling threads the vertical filling threads	 2 1 2 1
4	The number of threads per spool	140
5	The number of warp threads , including; the main (frame) threads the main (filling) threads the add horizontal filling threads the vertical filling threads	840 280 140 280 140
6	The width of the filling of comb, cm	25
7	The number of comb	42
9	The number of thread passing through the teeth of comb	8
10	The number of harness	12

Table 2. Comparative structural characteristics of layered-frame fabrics with and without filler warp threads.

№	Indicators	Laminated frame fabric with additional threads	Laminated frame fabric without additional threads
1	The Linear density, gr/km: -the main threads. -the wefts	 58,8x16 600x2	 58,8x16 600x2
2	The Density of Main Threads, threads/dm: - the main (frame) threads -the main (filling) threads -the add horizontal filling threads -the vertical filling threads	 88,0 46,6 46,6 94 102,6	 88,0 46,6 - - 102,6
3	The Contraction of Main threads, %: -the main (frame) threads -the main (filling) threads -the add horizontal filling threads -the vertical filling threads	 6,6 77,0 60,2 1,7	 15,3 80,2 - -
4	Fabric thickness, mm	11,3	10,2
5	Volume weight, kg/cubic meter	442	218
6	Surface density, gram/square meter	609,8	240

CONCLUSIONS

1. The use of laminated frame fabrics with multilayer interlacing elements in the outer layers of composite materials, serving as reinforcement, effectively reduces the risk of delamination during both fabrication and operation. This contributes to enhanced reliability and extended service life of the resulting products.

2. Layered-frame fabrics incorporating filler warp threads can achieve increased rigidity, strength, and wear resistance when the threads and weave patterns are appropriately selected. In particular, combining a multilayer weave of rigid yarns for the outer layers with yarns possessing tailored physical and mechanical properties for the inner layers optimizes overall fabric performance.

3. Owing to the differences in processing and fiber composition among the various warp systems (frame, filler, and auxiliary threads), the warp must be supplied from separate beams to ensure proper fabric formation and structural integrity

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FIELD-ORIENTED APPLICATION OF ACOUSTIC EMISSION FOR EARLY CRACK DETECTION IN WELDED STEEL STRUCTURES

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ABSTRACT

This study investigates the applicability of the Acoustic Emission (AE) method for early crack detection under field conditions on a heavy-duty concrete mixer chassis. Failure to detect fatigue-induced cracks at an early stage in welded steel structures can lead to severe structural damage and safety risks. The AE method enables the detection of damage at the moment it occurs by capturing sudden energy releases within the material. In this study, a commercial AE sensor (R15α) and a low-cost V1 prototype sensor were evaluated together. MATLAB analyses showed that the normalized peak amplitude was measured as 1.0044 for the R15α sensor and 0.9243 for the V1 sensor, indicating that the V1 sensor produced 7.97% lower amplitude compared to R15α. However, the maximum correlation coefficient between the two sensors was found to be 1.000, demonstrating that their signal shape and timing almost perfectly overlap. The results show that the AE method is suitable for real-time early crack detection in heavy-duty chassis structures and that the V1 sensor provides a cost-effective alternative for field applications.

Keywords: Acoustic Emission, welded structures, early crack detection, field application, sensor comparison.

1. INTRODUCTION

Welded steel structures are critical components used in heavy-duty vehicles, construction machinery, pressure vessels, and industrial carrier systems that operate under high cyclic loading. Fatigue cracks frequently occur in the weld bead, root region, and heat-affected zone (HAZ), threatening the structural integrity of these systems. Cracks that initiate at the microscopic scale propagate under repeated loading and evolve into macroscopic damage, significantly reducing the load-bearing capacity of the equipment (Grosse & Ohtsu, 2008; Pollock, 2012; Shiwa & Ohtsu, 2000). Therefore, early detection of crack initiation is crucial for operational safety and maintenance efficiency in heavy-duty structures.

Conventional non-destructive testing (NDT) methods (UT, MT, PT, RT) are limited to periodic inspections and thus cannot capture the precise moment when crack initiation occurs (Scruby, 1987). These methods can identify visible or surface-adjacent defects, yet the early microscopic stages of fatigue cracks often remain undetected. With the advancement of real-time Structural Health Monitoring (SHM) techniques, the Acoustic Emission (AE) method has emerged as a prominent technology for early detection of fatigue damage. According to the ASTM E1316 standard, AE is defined as the detection of elastic waves generated by sudden energy releases within a material (ASTM E1316, 2020).

Experimental studies have demonstrated that AE parameter such as amplitude, energy, hit count, rise time, and frequency spectrum are directly linked to crack initiation and propagation mechanisms (Sachse & Kim, 1980; Gorman, 1991; Ohtsu, 2019; Miller & McIntire, 1987). Research on the frequency characteristics of AE signals indicates that resonance-type sensors operating within the 100–300 kHz frequency band exhibit high sensitivity to micro-cracks in welded steel structures (Shiwa & Ohtsu, 2000; Gorman, 1991). Furthermore, the ASTM E976 standard provides guidelines for verifying the frequency response of AE sensors, serving as a reference for proper sensor selection in field applications (ASTM E976, 2015).

Despite the proven effectiveness of AE in laboratory conditions, its applicability in field environments particularly in heavy-duty vehicles remains limited. Hydraulic motor vibrations, road-induced shocks, gearbox interactions, and environmental noise may elevate the noise floor of AE measurements and adversely affect signal accuracy (Shinde & Ravisankar, 2020; Chen et al., 2021). Therefore, sensor placement, coupling materials, filtering strategies, and signal processing techniques must be specifically optimized for real field conditions.

Concrete mixer trucks are especially prone to fatigue damage due to the continuous rotational torque, hydraulic drive mechanisms, and variable dynamic loads acting on the chassis. Dynamic effects originating from the rotating drum, gear reducer, and chassis vibrations further complicate the AE measurement environment by introducing additional noise sources. The number of studies directly investigating the application of the AE method on heavy-duty concrete mixer structures is highly limited in the literature, which highlights the novelty and relevance of the present study.

In this study, the applicability of the Acoustic Emission method on a heavy-duty concrete mixer chassis under real field conditions is comprehensively investigated. The innovative contributions of this work can be summarized as follows:

- The AE method is applied under real operating conditions on a high-vibration heavy-duty vehicle.
- The commercial R15α sensor and a cost-effective V1 prototype sensor are compared under identical working conditions.

- Field AE signals are analyzed in the MATLAB environment using time–frequency domain techniques.
- The influence of field noise sources on signal quality is evaluated, and suitable band-pass filter ranges are identified.
- Field findings are compared with laboratory data from previous studies, and the applicability of AE for early crack detection in heavy-duty vehicles is discussed in detail.
- This study fills an important gap in the literature regarding the field applicability of the AE technique on heavy-duty vehicles and provides valuable insights for industrial structural health monitoring applications.

2. METHOD

This section presents the experimental setup, sensor structures, the effect of field conditions on AE signals, the data acquisition system, and signal processing methods in detail.

2.1 Experimental Setup

Heavy-duty concrete mixer chassis are complex metal structures that operate under continuous vibration, bending moments, torsion, and impact loads. Therefore, noise sources in AE measurements are abundant. The chassis consists of two longitudinal beams, transverse cross-members connecting them, and multiple welded joints.

The most common regions where fatigue cracks initiate are:

- Connections between longitudinal beams and cross-members,
- Weld seams on the upper plate,
- Load-bearing console regions,
- The vicinity of lower mounting points.

Three areas near these locations were selected as critical regions, and sensor placement was planned accordingly. This section presents the experimental setup, sensor structures, the effect of field conditions on AE signals, the data acquisition system, and signal processing methods in detail (see Fig1 and Fig2).



Figure 1. AE sensors mounted on opposite sides of the concrete mixer chassis



Figure 2. Field deployment layout of the V1 sensors on the concrete mixer chassis

2.2 Sensors and Technical Specifications

Two sensors were compared in this study;

R15α Commercial Sensor

- Wide-band piezoelectric structure
- 150 kHz center frequency
- Industrial-grade metal housing
- High sensitivity and low noise level This sensor is considered a reference commercial solution in the AE literature.

V1 Prototype Sensor

- Low-cost prototype design
- Targets the same center frequency range
- Compact piezoelectric element
- Developed for field testing conditions

The purpose of the V1 sensor is to reduce the overall cost of AE systems while maintaining sufficient measurement accuracy for practical applications.

2.3 Sensor Placement

The placement of sensors directly affects the accuracy of AE measurements. Sensor positions were selected by considering wave propagation paths, weld geometry, and vibration transmission routes.

Installation procedure:

1. The surface was ground to remove paint and irregularities.
2. Surface roughness was reduced using 800-grit sandpaper.

3. A thin layer of acoustic coupling gel was applied.
4. The R15α sensor was fixed using its magnetic base.
5. The V1 sensor was mounted using a bolted clamping mechanism.

This procedure is critical for minimizing transmission losses in AE signals (see Fig-3-4-5).



Figure 3. Positioning of the R15α sensor on the contact surface near the weld zone



Figure 4. Mounting mechanism used in the installation of AE sensors



Figure 5. Mounting and wiring layout of the R15α and V1 sensors

2.4 Data Acquisition System

AE data were collected using a portable AE unit with a sampling frequency of 1 MHz.

Key settings used:

- Sampling frequency: 1 MHz
- Digital band-pass filter: 40–400 kHz
- Preamplifier gain: 40 dB
- Trigger level: 45 dB (avg.)
- Recording mode: continuous data acquisition

This configuration provides sufficient resolution to distinguish AE signals from environmental noise.

2.5 Signal Processing

The analytical formulations used in this section are based on standard AE signal processing definitions. The energy and frequency-center expressions in Equations (1) and (2) follow the conventional formulations presented by Grosse and Ohtsu (2008) and Ohtsu (2019), while the cross-correlation definition in Equation (3) is based on classical digital signal processing theory described by Oppenheim and Schafer (1999).

AE signals were analyzed in MATLAB. The analyses were divided into three main categories.

2.5.1 Time-Domain Analysis

AE energy is calculated using Equation (1):

Equation (1): $E = \Sigma V_i^2$

This expression represents the sum of squared signal amplitudes and provides information about burst energy.

2.5.2 Frequency-Domain Analysis

The frequency-weighted center frequency is computed using Equation (2):

Equation (2): $f_{(c)} = (\Sigma f_i A_i) / (\Sigma A_i)$

This formula is used to detect shifts in the frequency response of the sensors.

2.5.3 Correlation Analysis

The time alignment between two sensors was examined using cross-correlation.

Equation (3): $R_{(xy)}(\tau) = \Sigma x(t) \cdot y(t + \tau)$

The peak at delay τ indicates the time shift between the two sensor signals (Equ-3).

3. RESULTS

This section presents sensor comparisons, MATLAB results, noise analysis of field measurements, and the overall performance evaluation of both sensors (see Fig-6-7-8).

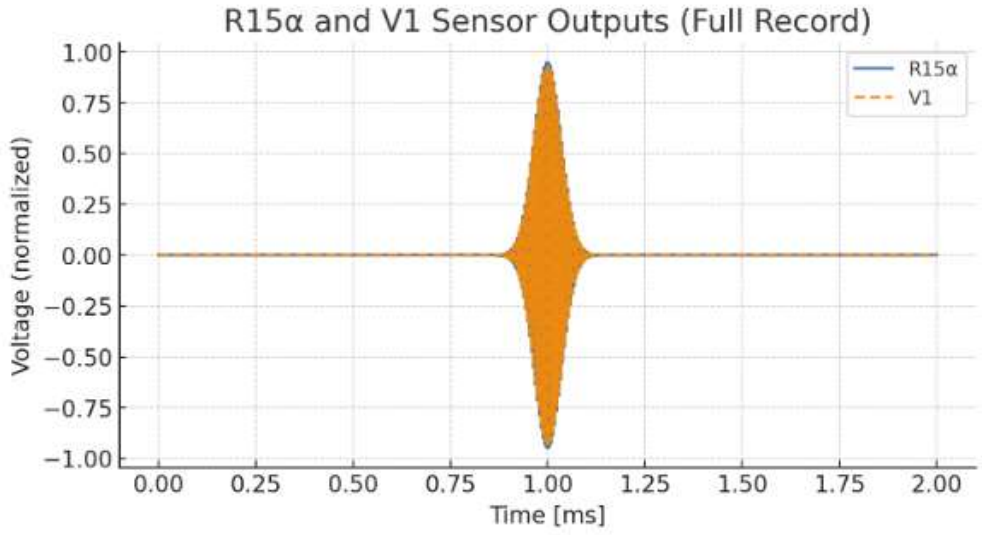

Figure 6. Time-domain signal comparison between the R15α and V1 sensors

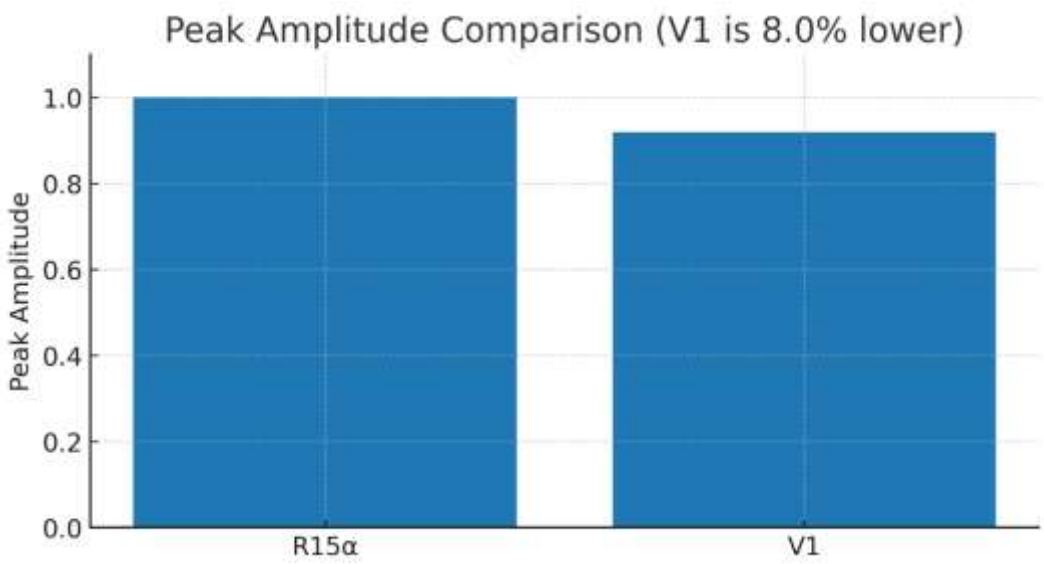

Figure 7. Zoomed view of the AE burst signal and the peak amplitude difference between the sensors

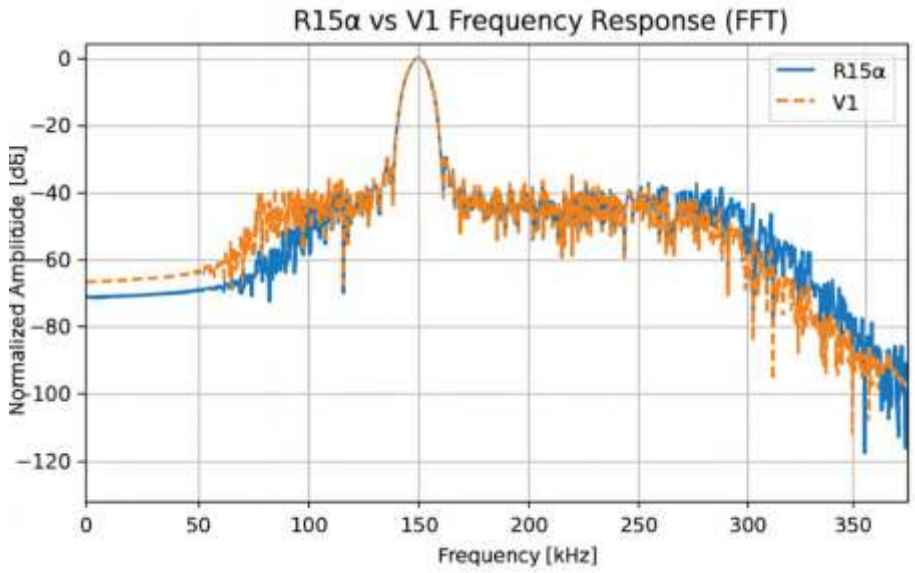

Figure 8. Comparison of the frequency spectra of the R15α and V1 sensors

AE bursts were recorded and normalized separately for both sensors. The results are as follows:

- R15α peak amplitude: 1.0044
- V1 peak amplitude: 0.9243
- Amplitude difference: 7.97% (V1 lower)
- Maximum correlation: 1.000

These results demonstrate that the V1 sensor exhibits nearly identical signal shape performance compared to the R15α.

3.1 Field Noise Analysis

During concrete mixer operation, several noise sources were present:

- Hydraulic motor noise,
- Drum rotation-induced vibrations,
- Vehicle aerodynamic noise,
- Chassis resonances.

Despite the vibration and noise in field conditions, the AE method was successfully implemented.These factors complicate AE signal interpretation. Therefore, filtering and threshold adjustments were critical. The signal-to-noise ratio (SNR) of field data was measured to be between 18–22 dB.

3.2 Sensor Comparison

The performance of both sensors can be summarized as follows:

- R15α: higher amplitude, industry-standard detection capability
- V1: low cost + high correlation advantage
- Both sensors exhibit excellent time alignment

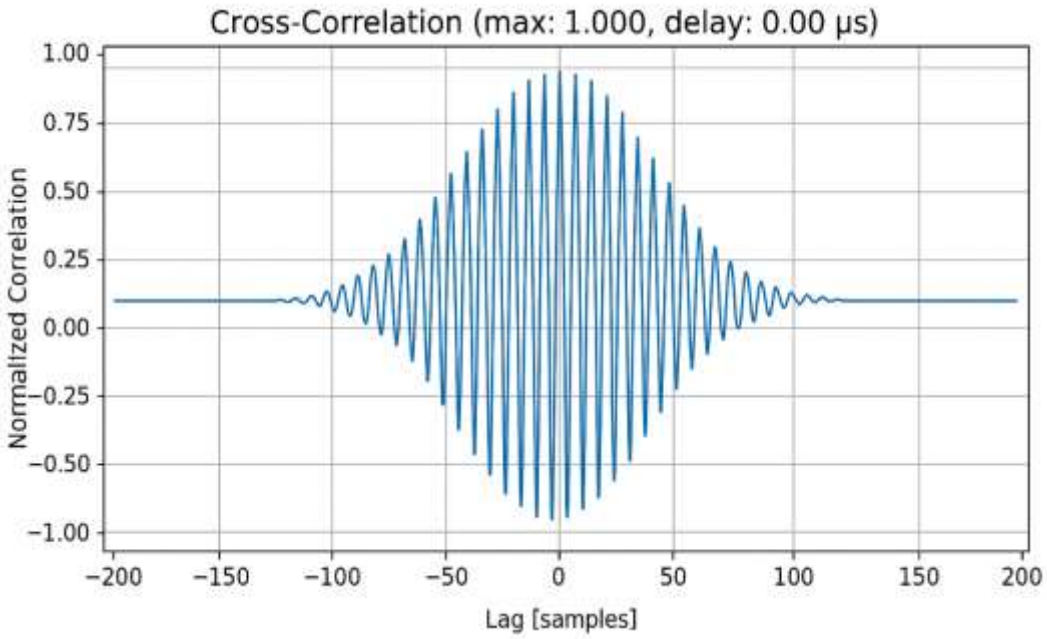

Figure 9. Cross-correlation plot between the R15α and V1 sensor signals

Although the V1 sensor is lower-cost, it demonstrates high accuracy in terms of signal shape and timing (see Fig-9).

4. DISCUSSION AND GENERAL EVALUATION

Despite challenging field conditions, the AE method provided reliable results. The V1 sensor's low-cost design, combined with its strong correlation with R15α, indicates substantial potential for industrial applications. The AE method is significantly more effective than classical NDT techniques in detecting the onset of crack formation.

4.1 Field Performance of the AE Method

Field tests demonstrated that:

- AE signals can be accurately distinguished even in high-noise environments.
- Noise generated by vibrations, mechanical impacts, and hydraulic motors can be controlled through filtering techniques.
- Despite field noise, the signal-to-noise ratio (SNR) remained in the range of 18–22 dB, which is sufficient for AE detection.
- Fatigue cracks in weld zones were observed to produce AE activity at early stages.

4.2 Importance of the AE Technique for Structural Health Monitoring

The AE method is superior to classical inspection techniques due to its continuous monitoring capability, detection of damage at the moment it occurs, and ability to localize sources. (Scruby, 1987; Miller & McIntire, 1987).

Engineering advantages include:

- Integration into early warning systems
- Reduction of unexpected downtime
- Decreased maintenance costs
- Detection of structural damage before it propagates

4.3 Recommendations for Future Work

- Source localization can be achieved using multi-sensor layouts.
- Sensitivity of the V1 sensor may be improved by testing different prototype variants.
- Machine learning methods can be applied for AE signal classification.
- Different loading conditions on the chassis can be evaluated.
- Field tests can be extended to other vehicle types.

5. CONCLUSIONS

This study comprehensively investigated the applicability of the Acoustic Emission (AE) method for early crack detection on a heavy-duty concrete mixer chassis. The advantages of AE in structural health monitoring were successfully validated despite challenging field conditions. Sensor comparisons, the influence of field noise on AE measurements, and MATLAB analyses provided valuable engineering insights.

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X-IŞINI GÖRÜNTÜLERİNDE TİBİA PLATO KIRIKLARINI TANIMLAMAK İÇİN DERİN ÖĞRENME MODELİ GELİŞTİRİLMESİ

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ÖZET

İnsan vücudu birçok kemik türünden oluşur. Bu kemiklerde meydana gelen kırıkların hızlı tespiti büyük önem taşımaktadır. Tibia plato kırığı diz eklemi içindeki proksimal tibiada meydana gelen bir kırığı ifade eder. Geleneksel X-ışını görüntülemesi, ortopedik uygulamalarda kırık tanımada sıkça kullanılmakta olup hızlı ve basit avantajlar sunar. Ancak, artan tıbbi talep ve sınırlı sağlık kaynakları klinisyenler üzerinde baskı oluşturarak yanlış tanı riskini artırmaktadır. Bu nedenle, kırıkların hızlı tespiti için güvenilir yardımcı yöntemler geliştirmek gün geçtikçe önemli hale gelmiştir. Yapay zekâ ve özellikle evrişimli sinir ağları (ESA), görüntü analizinde üstün özellik çıkarma ve desen tanıma yeteneği sunarak tıbbi tanı süreçlerinde devrim yaratmaktadır. Çalışmamız kapsamında ESA modelleri kullanılarak Tibia plato kırığı tespiti için yumuşak oylama temelli yeni bir yöntem ortaya koyulması hedeflenmiştir. Bu amaçla tibia plato kırığı olan 260 adet Ön, 260 adet Yan çekim X-Ray görüntüsü ve herhangi bir kırık bulgusu olmayan 260 adet normal X-Ray görüntüsü kullanılmıştır. Veri seti, önerilen ESA modellerini eğitmek, doğrulamak ve test etmek için rastgele eğitim (%70), doğrulama (%15) ve test (%15) olmak üzere üç kümeye ayrılmıştır. ResNet101, EfficientNetb0, DenseNet201, ShuffleNet ve VGG16 gibi literatürde kullanılan ve farklı problemlerde başarılı sonuçlar sağlayan ESA mimarileri kullanılmıştır. İlk olarak yukarıda bahsedilen 3 farklı ESA modeli tibia plato kırığı tespiti için Ön ve Yan X-Işını görüntülerinin eğitim ve doğrulama veri setleri kullanılarak ayrı ayrı eğitilmiştir. Eğitilen modellerin Ön ve Yan X-Işını görüntüleri kullanılarak elde edilen tahmin sonuçları yumuşak oylama ile birleştirilmiş ve her bir mimari için nihayi karar elde edilmiştir. Tüm modeller için %80 ile %91 arasında tibia plato tespit doğruluğu elde edilmiştir. Elde edilen bu performans önerilen ESA temelli yöntemin tibia kırığı tespitinde umut verici olduğunu göstermektedir.

Anahtar Kelimeler: Tibia plato kırığı, yapay zeka, evrişimli sinir ağları, yumuşak oylama, karar destek sistemleri

DEVELOPMENT OF A DEEP LEARNING MODEL TO IDENTIFY TIBIA PLATEAU FRACTURES ON X-RAY IMAGES

ABSTRACT

The human body is composed of many types of bones. Rapid detection of fractures in these bones is crucial. A tibial plateau fracture refers to a fracture that occurs in the proximal tibia within the knee joint. Conventional X-ray imaging is frequently used for fracture diagnosis in orthopedic practice, offering the advantages of speed and simplicity. However, increasing medical demand and limited healthcare resources put pressure on clinicians, increasing the risk of misdiagnosis. Therefore, developing reliable ancillary methods for rapid fracture detection has become increasingly important. Artificial intelligence, and in particular convolutional neural networks (CNNs), are revolutionizing medical diagnostic processes by offering superior feature extraction and pattern recognition capabilities in image analysis. Our study aimed to develop a new soft-voting-based method for detecting tibial plateau fractures using CNN models. For this purpose, 317 anteroposterior and 317 lateral X-ray images with tibial plateau fractures and 339 normal X-ray images without any fracture findings are used. The dataset is randomly divided into three sets, namely training (70%), validation (15%), and testing (15%), to train, validate, and test the proposed CNN models. CNN architectures such as ResNet101, EfficientNetb0, DenseNet201, ShuffleNet, and VGG16, which are used in the literature and provide successful results in different problems, are used. First, the three different CNN models mentioned above are trained separately for tibial plateau fracture detection using training and validation datasets of frontal and lateral X-ray images. The prediction results obtained from the trained models using frontal and lateral X-ray images are combined using soft voting to obtain the final decision for each architecture. Tibial plateau detection accuracies between 80% and 91% are achieved for all models. This performance shows that the proposed CNN-based method is promising in the detection of tibia fractures.

Keywords: Tibial plateau fracture, artificial intelligence, convolutional neural networks, soft voting, decision support systems

1. INTRODUCTION

The human body is composed of various types of bones. The tibial plateau, located immediately below the femur, is the topmost portion of the tibia, the larger of the two lower leg bones. The term "tibial plateau fracture" (TPF) describes a fracture in the proximal tibia within the joint. This disorder is a serious articular injury that frequently results in considerable damage to the locomotor system, which limits joint functionality and produces worse than ideal clinical outcomes (Cho et al., 2017; Schulak and Gunn, 1997). The proximal tibia is vulnerable to several structural injuries, such as compression fractures, split fractures, bone deformities, or other damage brought on by severe traumatic loading, because it is a crucial location for force transmission in the lower leg (Hofmann et al., 2020; Xie et al., 2020).

Fractures at the top part of the tibia are usually complicated and frequently involve other knee components, including the meniscus, surrounding nerves, joint surface, and vascular tissues. Because treatment has a major impact on the patient's mobility and long-term quality of life, careful planning is necessary. The main diagnostic technique for TPFs is conventional X-ray imaging, which is prized for its ease of use, speed, and simplicity. Orthopedic doctors must accurately interpret X-ray images in order to ensure appropriate diagnosis and treatment. However, rising medical service demands and resource constraints can put pressure on clinicians, increasing the risk of missed or incorrect diagnoses, particularly with subtle fractures that may not be readily visible on X-rays (Liu et al., 2021). According to research, misinterpretation rates in radiography reach 40% due to severe, time-sensitive conditions and contributing factors such as recalcitrant patients and hasty decision-making. The serious health dangers associated with this circumstance highlight the necessity of trustworthy techniques for orthopedic professionals to quickly identify TPF (Guly, 2001; Pinto et al., 2016).

Computer science, mathematics, cybernetics, and determinism are all combined in the multidisciplinary field of artificial intelligence (AI). It is regarded as a 21st-century breakthrough technology that profoundly changes international operational frameworks. AI's main objective is to research human intelligence (HI) to create intelligent algorithms that let computers imitate and even surpass human cognitive capacities (Myers et al., 2020). AI, particularly in image analysis, has greatly evolved with the development of machine learning (ML), deep learning (DL), and convolutional neural networks (CNNs). Applications in computer vision, speech recognition, natural language processing, decision-making, and massive data analysis—particularly in the medical field—have resulted from artificial intelligence's adaptability (Wang et al., 2019). Research has demonstrated the efficacy of AI in imaging evaluations of orthopedic diseases such as scoliosis (Chen et al., 2021), osteoarthritis (Norman et al., 2019), and ligament injuries (Pedoia et al., 2019), as well as tumor identification (Wang et al., 2019).

Features like the femoral neck-shaft angle, intensity gradient, Gabor texture, and Markov Random Field texture are employed in one of the first investigations on fracture diagnosis. Support vector machines (SVM) and a Bayesian classifier are used, and combining various features and classification methods produced better outcomes than utilizing just one feature or classifier (Lim et al., 2004). Several image processing algorithms, such as corner and edge detection, are used in another related work to extract important and unique characteristics. A SVM classifier is then used to classify these features, resulting in a high degree of accuracy (Avinash Vishnu et al., 2015).

Our goal is to use state-of-the-art CNN models to create a novel soft-voting-based technique for tibial plateau fracture detection. For this, two distinct image datasets—anteroposterior (AP) and lateral (Lat)—that contained x-ray images with and without fractures are used.

2. MATERIALS AND METHOD

Within the scope of our study, it is aimed to present a new method based on soft voting for the detection of tibial plateau fractures from X-Ray images using Convolutional Neural Networks. The processing steps of the proposed method are given in Figure 2.1.

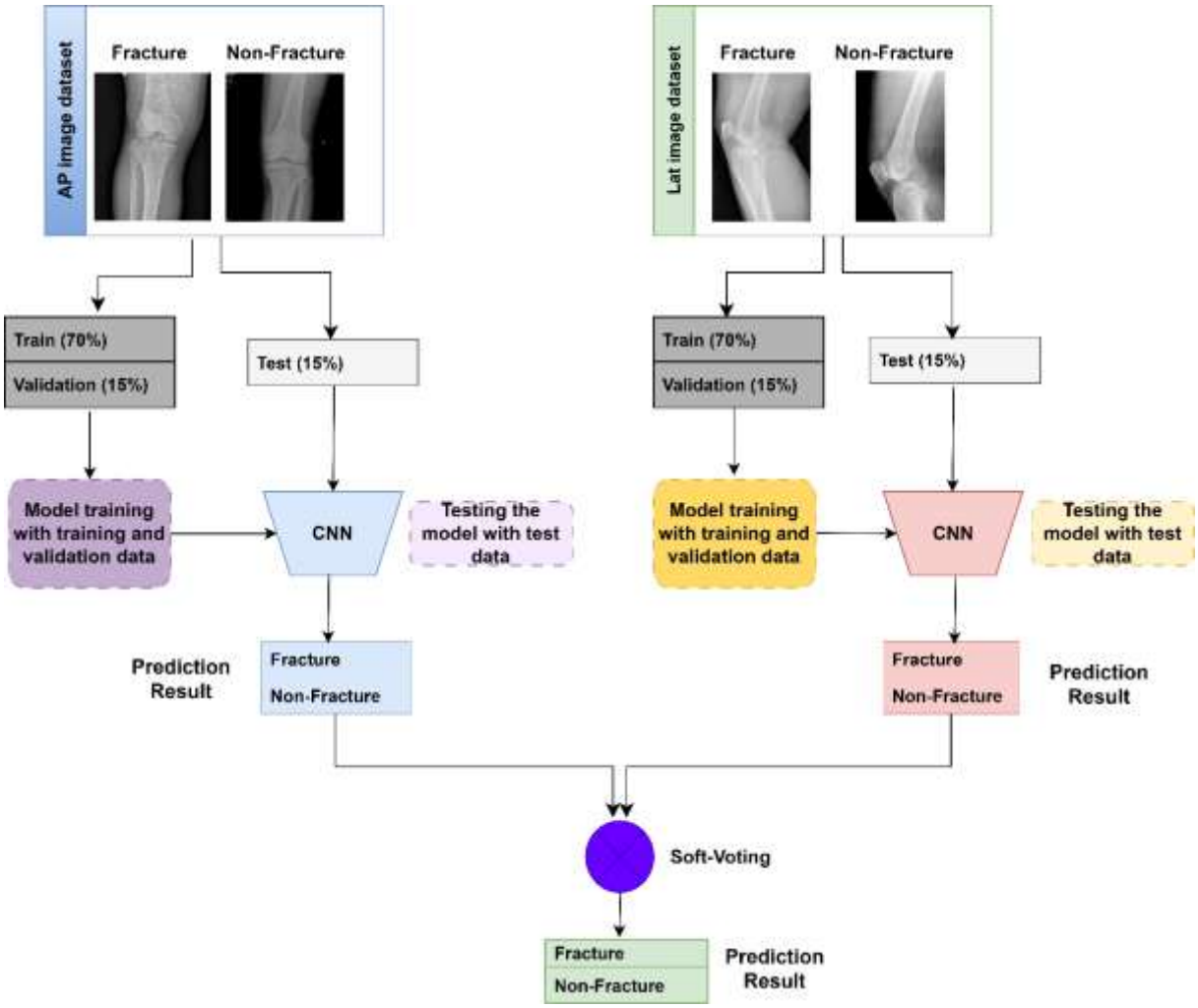

Figure 2.1. The overall framework of the proposed model.

2.1. Description of Datasets and Data Preprocessing

This study included adult patients (aged 18 years or older) diagnosed with tibial plateau fractures in the emergency department. These patients' X-Ray images are retrospectively reviewed, and their X-ray data are captured and recorded. 339 normal X-ray images without any fracture findings and 317 AP and 317 Lat X-ray images with tibial plateau fractures are used for the proposed study.

The input images are reduced to 224,224 pixels during the preprocessing stage in order to conform to the dimensions of the input layer of the applicable deep learning architecture. The complete dataset is then divided into three sets at random in order to train, validate, and test the suggested network. In this case, the training, validation, and test sets receive 70%, 15%, and 15% of the total data.

2.2. Tibial plateau fracture detection architecture

Convolutional neural network architectures, including ResNet101, EfficientNetb0, DenseNet201, ShuffleNet, and VGG16, which have been applied in the literature and have produced effective outcomes in a variety of tasks, are used in this study.

ResNet is an image recognition model that achieves notable improvements by using shortcut connections and deep residual learning. The residual block, which incorporates two convolutional layers and an activation function like ReLU, is its core component. By giving gradients an alternate and direct channel, these novel skip connections successfully address the vanishing gradient issue that is prevalent in deep networks. This increases accuracy, especially in classification, and speeds up training while lowering gradient issues. Additionally, ResNet makes an effort to comprehend the significance of acquired features by successfully lowering the weight of those that are thought to be unimportant for the task. However, because of dimensionality, adding additional skip connections may make the architecture more complex. Medical image processing often uses popular ResNet variants as ResNet18, ResNet50, and ResNet101. In our research, the ResNet101 architecture is employed (Salehi et al., 2023; Subasi, 2022). EfficientNet is an CNN model that leverages composite coefficients to reliably scale the depth, width, and resolution of the model. Initially, a base model, EfficientNetB0, containing convolutional and mobile reverse bottleneck (MB) convolutional blocks, was discovered via neural architecture search. In order to enhance its performance, this base model was subsequently scaled to larger models, ranging from EfficientNetB1 to B7. EfficientNetB0 is utilized in our investigation (Mahbod et al., 2025). ShuffleNet is an efficient CNN that seeks to achieve excellent accuracy on mobile devices with limited processing power while minimizing computational costs. It uses two key architectural innovations: pointwise group convolution (GConv), which reduces complexity by replacing traditional convolutions with discrete group convolutions, and the channel shuffle operation, which allows information to move across groups to increase feature capture. ShuffleNet outperforms lightweight approaches in terms of accuracy and computing complexity (Fang et al., 2022). DenseNet is an ESA-based model utilized in applications like medical image classification and retrieval. It enhances gradient flow by extending ResNet's skip connections through feedforward connections between all layers. The architecture includes dense blocks with multiple interconnected layers and transition layers for convolution and pooling. Notably, DenseNets maintain strong performance even at shallow depths, setting them apart from conventional network designs DenseNet201 is utilized in our investigation (Mahbod et al., 2025; Subasi, 2022). The design of the Visual Geometry Group (VGG) clearly demonstrates a trend toward deeper networks. These networks have been built with various layer configurations, from 11 to 19, but the most successful versions contain 16 or more layers. Performance is significantly improved by using smaller filter sizes throughout the network with greater depth. VGG uses a 2x2 pooling area and 3x3 convolutional filters. For convolution operations, stride and padding are set to 1. For pooling, stride=2 is used. After each pooling layer, the number of filters is often doubled; this is a notable aspect of the VGG architecture. VGG16 is utilized in our investigation (Mahbod et al., 2025; Subasi, 2022).

First, utilizing training and validation datasets of AP and Lat images, the distinct CNN models are trained independently for tibia plateau fracture detection. The test datasets are then used to evaluate the trained architectures' performance. We sought to improve classification performance using an ***ensemble learning*** approach in addition to the architectures' individual performance on the two image datasets. Combining multiple models to provide a final forecast that is more accurate and dependable than a single model is known as ensemble learning. This

method improves generalization to unknown data while utilizing the benefits of many models. A better combination of performance, efficiency, and memory can only be attained by selecting the finest CNN models and figuring out how to combine them. The literature discusses three ensemble learning techniques: weighted voting, ***soft voting***, and hard voting. ***Soft voting***: The predicted class probabilities are used in place of the class labels derived from each model (label 0 for the non-fracture image and label 1 for the fracture image). To choose the class with the highest probability, the ensemble learning approach averages or adds the probabilities. This approach often yields superior results by accounting for each model's degree of confidence in its predictions. In our study, individual results obtained from AP and Lat images using CNN architectures are used to obtain a general result with the soft voting approach.

2.3 Performance Evaluation

The performance of the trained CNN models is evaluated using a number of parameters, including accuracy (ACC), sensitivity (SEN), specificity (SPE), precision (PRE), and the Area Under the Receiver Operating Characteristic Curve (AUC-ROC).

$$SEN = \frac{TP}{TP + FN}$$
$$SPE = \frac{TN}{TN + FP}$$
$$PPV = \frac{TP}{TP + FP} \quad (1)$$
$$ACC = \frac{TP + TN}{TP + TN + FP + FN}$$

These metrics are derived from the confusion matrix's four components: True Positive (TP): Accurately classified fracture samples. True Negatives (TN) are Non-Fracture samples that have been correctly identified. False Positive (FP): When fracture is mistakenly diagnosed in Non-Fracture samples. False Negative (FN): Fracture samples that are incorrectly classified as Non-Fracture (Cura et al., 2023).

3. RESULTS AND DISCUSSION

This paper suggests an ensemble approach based on soft voting for the identification of tibial plateau fractures using CNNs. A dataset of 317 pairs of tibial plateau fractures and 339 normal X-ray images is presented in the study. Training (70%), Validation (15%), and Test (15%) sets are created by resizing the images to 224x224 pixels. Both AP and Lat image datasets are used to train five CNN architectures: ResNet101, EfficientNetb0, DenseNet201, ShuffleNet, and VGG16. Among the innovations is an ensemble approach that combines forecasts from these CNNs using soft-voting. By evaluating the model's performance using criteria like ACC, SEN, SPE, PPV, and AUC-ROC, a strong foundation for identifying tibial plateau fractures utilizing cutting-edge deep learning techniques is established.

Table 3.1. Classification performance using several CNN techniques, image datasets ans Soft-Voting.

		Validation					Test				
		ACC	SEN	SPE	PPV	FDR	ACC	SEN	SPE	PPV	FDR
ResNet101	AP	90.80	87.20	94.10	93.20	6.80	85.90	89.60	82.40	82.70	17.30
	Lat	89.80	87.20	92.20	81.10	8.90	84.80	93.80	76.50	78.90	21.10
	Soft-Voting	93.90	89.40	98.00	97.70	2.30	***90.90***	***91.70***	***90.20***	***89.80***	***10.20***
EfficientNetb0	AP	88.80	89.40	88.20	87.50	12.50	81.80	85.40	78.40	78.80	21.20
	Lat	88.80	78.70	98.00	97.40	2.60	82.80	77.10	88.20	86.00	14.00
	Soft-Voting	89.80	85.10	94.10	93.00	7.00	86.90	85.40	88.20	87.20	12.80
DenseNet201	AP	90.80	87.20	94.10	93.20	6.80	86.90	85.40	88.20	87.20	12.80
	Lat	86.70	83.00	90.20	88.60	11.40	82.80	85.40	80.40	80.40	19.60
	Soft-Voting	94.90	89.40	100.00	100.00	0.00	86.90	85.40	88.20	87.20	12.80
ShuffleNet	AP	90.80	89.40	92.20	91.30	8.70	85.90	87.50	84.30	84.00	16.00
	Lat	86.70	83.00	90.20	88.60	11.40	80.80	83.30	78.40	78.40	21.60
	Soft-Voting	89.80	85.10	94.10	93.00	7.00	88.90	91.70	86.30	86.30	13.70
VGG16	AP	89.80	91.50	88.20	97.80	12.20	81.80	87.50	76.50	77.80	22.20
	Lat	90.80	83.00	98.00	97.50	2.50	89.90	89.60	90.20	89.60	10.40
	Soft-Voting	91.80	89.40	94.10	93.30	6.70	87.90	91.70	84.30	84.60	15.40

The classification performance of five distinct CNN architectures (ResNet101, EfficientNetb0, DenseNet201, ShuffleNet, and VGG16) for identifying tibial plateau fractures are shown in Table 3.1. The final Soft-Voting ensemble from both the Validation and Test datasets, as well as images from AP (Anteroposterior) and Lat (Lateral), are displayed. The Soft-Voting ensemble consistently and significantly improved performance across almost all models and metrics, particularly on the independent test dataset. This is the most important finding from the table. Test set performance is used to assess model generalization, and soft-voting results highlight important discoveries. ResNet101 performs well in recognizing both fracture and non-fracture cases, achieving the greatest ACC (90.90%) and SPE (90.20%), as well as high SEN (91.70%). The efficacy of the ensemble strategy is validated by the Soft-Voting approach, which likewise consistently increases test ACC when compared to individual model results. Lat models, including ResNet101 Lat (93.80% SEN) and VGG16 Lat (89.60% SEN), outperformed AP models in the test set, suggesting that lateral pictures contain crucial information for fracture diagnosis. With VGG16 AP hitting 22.20%, the FDR İs noticeably high. ResNet101's decrease from 17.30%/21.10% to 10.20% is an example of how Soft-Voting decreased test FDR for all models. When moving from the validation to the test set, performance decreased, underscoring the difficulties with unknown data. The study demonstrates that the soft-voting ensemble learning strategy is successful in identifying tibial plateau fractures, with ResNet101 emerging as the best model with a test ACC of 90.90% and the best balance between SPE and SEN.

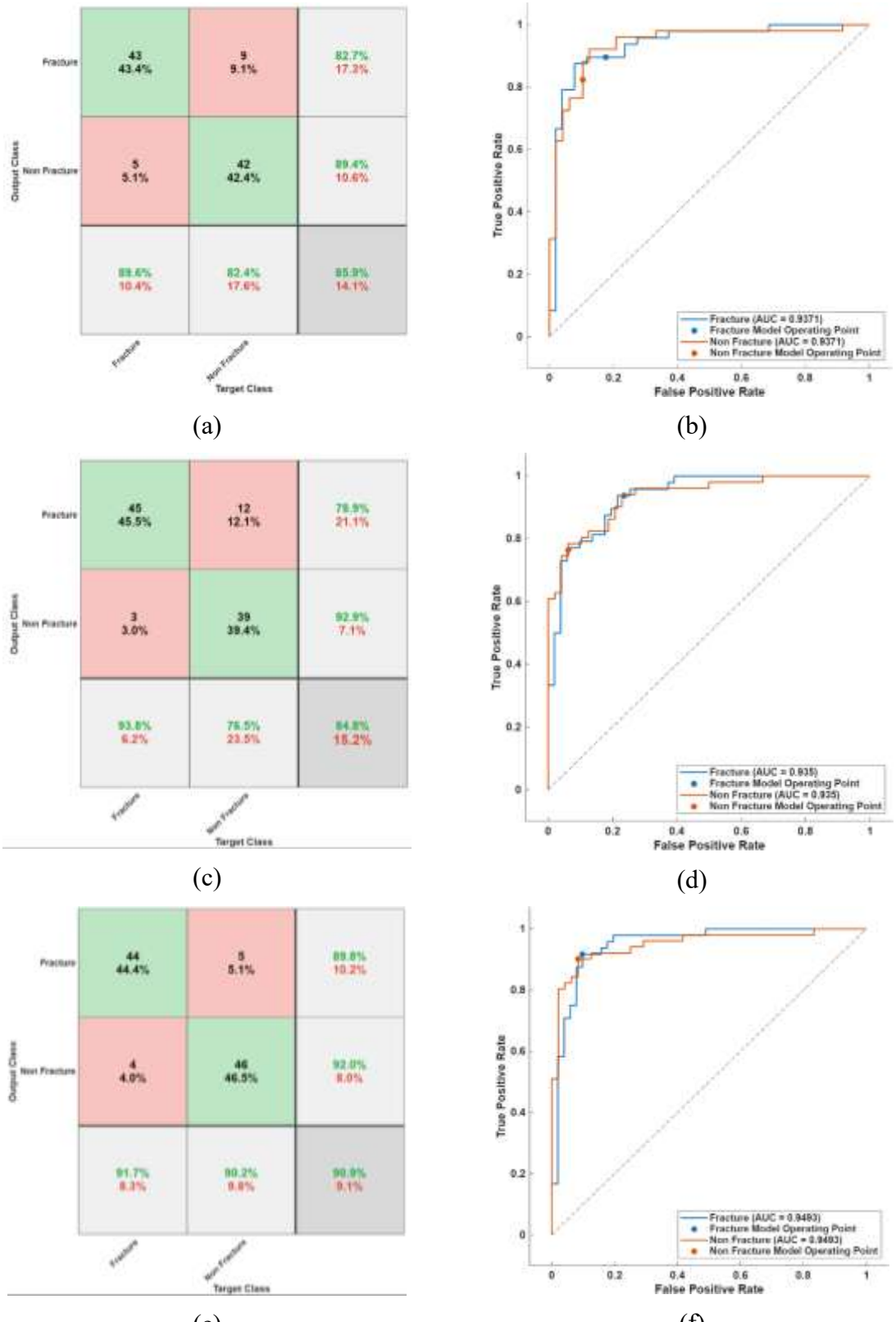

Figure 3.1. For test case of ResNet101: a) Confusion Matrix, b) ROC curve, and AUC value obtained for the App image dataset; c) Confusion Matrix, d) ROC curve, and AUC value obtained for Lat image dataset; e) Confusion Matrix, f) ROC curve, and AUC value obtained for the Soft-Voting

The ResNet101 architecture's comprehensive classification performance on the test dataset for AP image dataset (a, b), Lat image dataset (c, d), and the Soft-Voting (e, f) is shown in Figure 3.1. The Confusion Matrices (a, c, e) and Receiver Operating Characteristic (ROC) Curves with their corresponding Area Under the Curve (AUC) values (b, d, f) are the main subjects of the evaluation. The Soft-Voting model performs the best overall for fracture diagnosis, according to important findings from the study of confusion matrices. In comparison to the other models, it obtains the greatest True Positive rate (91.7%) and True Negative rate (90.2%), with a balanced decrease in False Positives. The Soft-Voting model has the highest AUC (0.9493), indicating superior discrimination ability, as shown by the ROC curve and AUC analysis. With AUCs above 0.930, all models perform well and show good classification abilities. Overall, the Soft-Voting model significantly enhances the predictive quality of the ResNet101 architecture, making it the most clinically dependable choice among the assessed configurations.

3. CONCLUSION

In order to automatically diagnose tibial plateau fractures in X-ray images, this study successfully designed and assessed a novel soft-voting-based ensemble method employing CNNs. Developing trustworthy ancillary techniques for quick fracture identification is becoming more crucial because to the demands on medical professionals and the possibility of incorrect diagnosis using traditional X-ray interpretation. Five well-known CNN architectures—ResNet101, EfficientNetb0, DenseNet201, ShuffleNet, and VGG16—are used in the study. Each CNN architecture is trained separately on both AP and Lat X-ray images. The effectiveness of integrating predictions is confirmed by the Soft-Voting ensemble technique, which consistently and considerably improved classification performance across nearly all models and metrics on the independent test dataset. With the greatest test ACC of 90.90% and the highest Specificity of 90.20%, the ResNet101 Soft-Voting ensemble proved to be the best overall model for generalized TPF identification. By reducing both missed fractures and false alarms, this model showed the most balanced prediction quality. In comparison to the individual AP (AUC 0.9371) and Lat (AUC 0.935) models, the Soft-Voting ensemble for ResNet101 likewise produced the highest Area Under the Curve (AUC) of 0.9493, demonstrating higher discrimination abilities between fracture and non-fracture cases. Because Lat models frequently obtained higher sensitivity than AP models, analysis of individual models revealed that Lat view images contain information essential for fracture diagnosis.

The Soft-Voting method effectively combined the advantages of both points of view. The suggested CNN-based soft-voting method achieved tibial plateau detection accuracies between 80% and 91% for all models, suggesting that this method is promising in the detection of tibia fractures and builds a strong foundation for a dependable decision support system in orthopedic practice. In conclusion, the suggested soft-voting ensemble approach is a reliable and promising supplementary tool for orthopedic practitioners, providing a significant increase in the precision and dependability of TPF diagnosis from X-ray pictures by optimizing deep learning.

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EEG'DEN ŞİZOFRENİ TESPİTİ: DERİN ÖĞRENME VE BEYİN BAĞLANTISI YAKLAŞIMI

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ÖZET

Şizofreni, sıklıkla beyin bağlantılarındaki değişikliklerle ilişkili olan, biliş, algı ve davranış bozukluklarıyla karakterize çok yönlü bir nöropsikiyatrik durumdur. Kapsamlı araştırmalara rağmen, temel nörofizyolojik mekanizmalar hala tam olarak anlaşılamamıştır. Elektrofizyolojik sinyal işleme ve nörogörüntüleme alanındaki son gelişmeler, şizofreninin ağ tabanlı bir şekilde incelenmesini kolaylaştırarak yaygın beyin işlev bozukluklarına dair içgörüler sağlamıştır. Bu çalışma, şizofreniyle ilişkili beyin ağı işlev bozukluklarını keşfetmek için derin öğrenmeyle birlikte EEG tabanlı işlevsel bağlantı analizini kullanmaktadır. Şizofreni hastaları ve sağlıklı kontroller arasındaki işlevsel bağlantı farklılıklarını analiz etmek için iki adet kamuya açık EEG veri setini kullanılmıştır. EEG kayıtları 10 saniyelik aralıklarla segmentlere ayrılmış ve her segment için yedi bağlantı parametresi hesaplanmıştır: çapraz güç spektral yoğunluğu, büyüklüğün karesi alınmış koherans, kovaryans, korelasyon katsayısı, korentropi katsayısı, koherentropi katsayısı ve faz kilitleme değeri. Çıkarılan bu bağlantı özellikleri, N×N boyutunda bağlantı matrisleri oluşturmak için kullanılmıştır; burada N, EEG kanal sayısıdır. Elektrot çiftleri arasındaki işlevsel bağlantı, ilgili özelliğe göre bu matrislerle temsil edilmektedir. Her bağlantı matrisi, derin öğrenme sınıflandırma amaçları için 224×224 piksellik bir görüntüye dönüştürülmüştür. Araştırmamızda, elde edilen bağlantı tabanlı görüntülerde dört farklı evrişimli sinir ağı mimarisinin (ResNet18, ResNet50, DenseNet201 ve ShuffleNet) sınıflandırma performansını karşılaştırmalı olarak değerlendirdik. Her iki veri seti üzerinde yürüttüğümüz deneysel araştırmaya göre, DenseNet201 ve ShuffleNet modelleri, çeşitli bağlantı değişkenleriyle birleştirildiğinde şizofreni tanısında büyük sınıflandırma başarısı göstermiştir. Bu yaklaşım, derin öğrenmenin görüntü işlemedeki güçlü yönlerinden yararlanmış ve şizofreniyle bağlantılı EEG bağlantı modellerinin etkili bir şekilde sınıflandırılmasını sağlamıştır.

Anahtar Kelimeler: Şizofreni, Elektroensefalografi (EEG), Fonksiyonel Bağlantı, Derin Öğrenme, Nörofizyolojik Biyobelirteçler, Sinyal İşleme

SCHIZOPHRENIA DETECTION FROM EEG: A DEEP LEARNING AND BRAIN CONNECTIVITY APPROACH

ABSTRACT

Schizophrenia is a multifaceted neuropsychiatric condition marked by impairments in cognition, perception, and behavior, frequently associated with altered brain connections. Despite comprehensive research, the fundamental neurophysiological mechanisms remain incompletely understood. Recent breakthroughs in electrophysiological signal processing and neuroimaging have facilitated a network-based investigation of schizophrenia, yielding insights into extensive brain dysfunctions. This study employs EEG-based functional connectivity analysis, combined with deep learning, to investigate brain network dysfunctions associated with schizophrenia. It employs two publicly available EEG datasets to analyze functional connectivity differences between patients with schizophrenia and healthy controls. EEG recordings are segmented into 10-second intervals, and seven connectivity parameters are computed for each segment: cross power spectral density, magnitude squared coherence, covariance, correlation coefficient, correntropy coefficient, coherentropy coefficient, and phase locking value. These extracted connectivity properties are used to create connectivity matrices of size N×N, where N is the number of EEG channels. These matrices represent the functional connectivity between electrode pairs according to the corresponding feature. Each connectivity matrix is transformed into a 224×224 pixel image for deep learning classification purposes. In our research, we comparatively evaluated the classification performance of four different convolutional neural network architectures (ResNet18, ResNet50, DenseNet201, and ShuffleNet) in the resulting connectivity-based images. DenseNet201 and ShuffleNet models, when combined with a variety of connectivity variables, demonstrated great classification success in schizophrenia identification, according to our experimental research conducted on both datasets. This approach takes advantage of deep learning's strengths in image processing and allows for the effective classification of EEG connectivity patterns linked with schizophrenia.

Keywords: Schizophrenia, Electroencephalography (EEG), Functional Connectivity, Deep Learning, Neurophysiological Biomarkers, Signal Processing

1. INTRODUCTION

Schizophrenia (SCH) is a chronic illness that causes delusions and hallucinations as well as a gradual decline in emotional behavior and cognitive function (Hassan, et al., 2023; Puri et al., 2025; Puri et al., 2026). Severe cognitive degeneration affected 25 million people globally in 2023, with those in their early twenties being particularly vulnerable. Long-term, costly medication strains families and healthcare systems, while misdiagnosis and treatment delays increase mortality (Puri et al., 2025; Puri et al., 2026). A dependable, affordable, and automated detection system is required (Hassan, et al., 2023; Puri et al., 2025; Puri et al., 2026).

The fundamental neurophysiological mechanisms of schizophrenia are still poorly understood despite decades of research. However, new developments in electrophysiological signal processing and neuroimaging have made it possible for researchers to study schizophrenia from a network-based approach, providing fresh perspectives on the disorder's altered brain dynamics. A popular non-invasive and temporally accurate technique for evaluating the electrical activity of the brain is electroencephalography (EEG). EEG is beneficial for investigating brain dynamics in mental illnesses like schizophrenia because of its great temporal resolution and affordability (Agarwal, and Singhal, 2023). Functional connectivity, which offers a way to evaluate synchronization and statistical interdependence across geographically diverse brain regions, has become a crucial framework in EEG research in recent years (Friston, 2011). The degree of collaboration between different brain regions is determined by functional connectivity, which makes it easier to comprehend the alterations in connectivity seen in conditions like schizophrenia. Schizophrenia patients' resting-state EEG investigations have shown decreased alpha activity in the frontal cortex along with elevations in delta, theta, and beta activity. This illustrates "hypofrontality," a condition that shows how the illness affects cognitive abilities (Ingvar, and Franzén, 1974; Ragland et al., 2007). Several signal processing methods, such as coherence, cross-power spectral density (CPSD), phase-locking value (PLV), correlation, covariance, correntropy, and cohentropy, can be used to evaluate functional connectivity in EEG data (Sarwer et al., 2025; Stam, and Reijneveld, 2007). These techniques aid in the discovery of possible biomarkers and advance knowledge of the altered connection patterns in the brain networks of people with schizophrenia. Patients with schizophrenia have often been found to exhibit altered patterns of functional connectivity, indicating aberrant integration of neural information across distant brain networks (Pettersson-Yeo et al., 20211). The disorder's cognitive and perceptual deficits are assumed to be caused by a disruption in large-scale brain synchronization, which is reflected in these abnormalities (Rubinov, and Sporns, 2010).

This research is focused on identifying changes in functional brain connectivity associated with schizophrenia symptoms. We will achieve this by analyzing EEG data using a novel framework that integrates signal processing, functional connectivity analysis, and deep learning analysis. The ultimate goal is to offer fresh insights into brain network dysfunctions and establish a critical foundation for developing neurophysiological biomarkers.

2. MATERIALS AND METHOD

Figure 2.1 illustrates the whole approach, which uses deep learning based on Electroencephalography (EEG) connectivity properties to classify SCH and CS. To eliminate artifacts and isolate pertinent times, the procedure starts with pre-processing operations including filtering and segmentation (e.g., into 10-second segments). To measure the functional relationships between different parts of the brain, several connectivity parameters are taken from EEG channels. These features are arranged into NxN connectivity matrices, which are then transformed into heatmap images to be fed into a pre-trained CNN architecture. Through

deep learning, the CNN improves diagnostic support by identifying high-level spatial patterns in these images and producing a binary diagnostic output of CS or SCH.

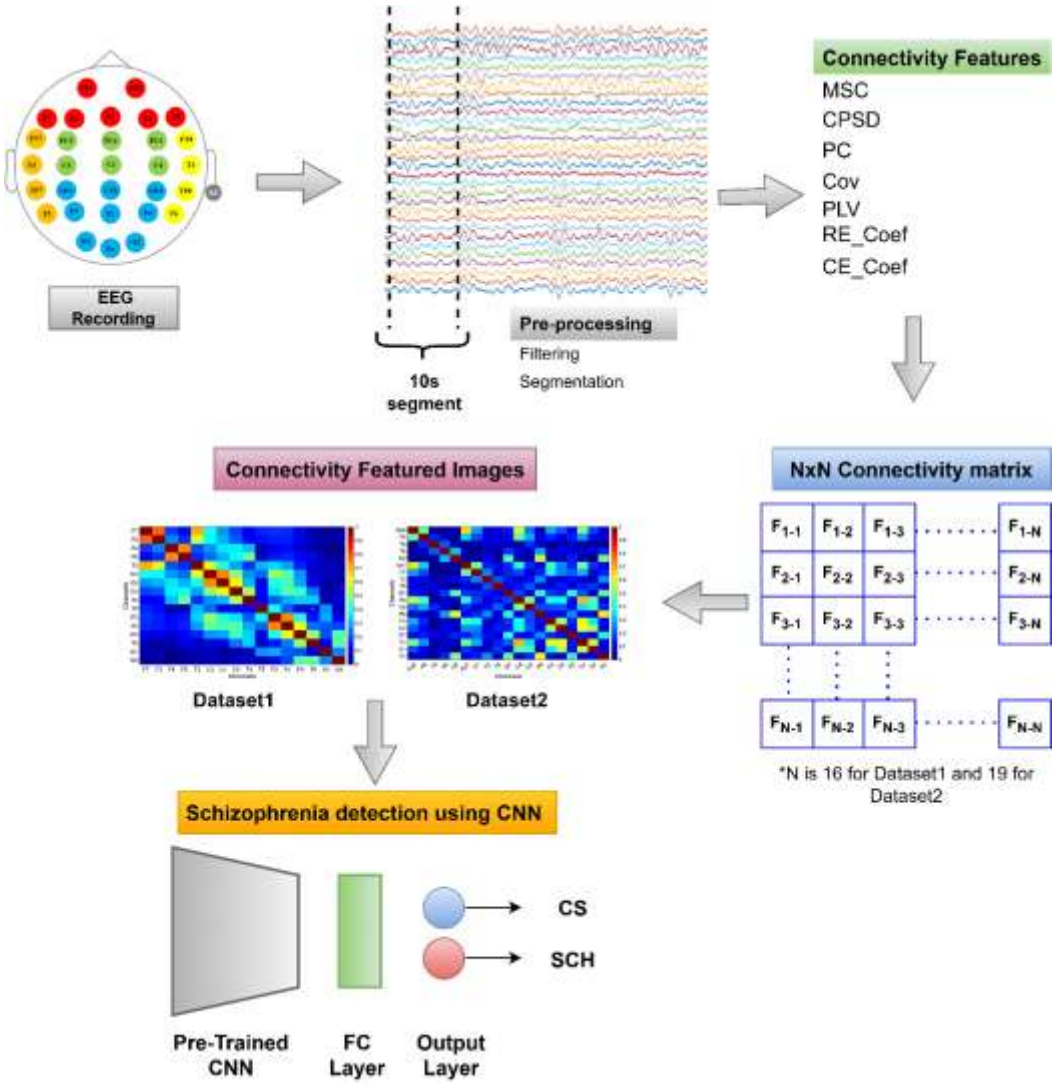


Figure 2.1. Block diagram of the suggested methodology

2.1. Description of EEG Datasets

This study examined functional connectivity differences between people with schizophrenia and healthy controls using two publicly available EEG datasets.

2.1.1 Schizophrenia EEG Datasets-1 (Dataset 1)

This study's initial dataset came from M.V. Lomonosov Moscow State University's Laboratory for Neurophysiology and Neuro-Computer Interfaces. It includes EEG recordings taken during resting-state conditions from 84 teenagers, ages 11 to 14. 39 healthy controls (CS) and 45 people exhibiting symptoms of schizophrenia (SCH) were the two groups of volunteers. Doctors at the Mental Health Research Center (MHRC) verified diagnoses for the schizophrenia group using the ICD-10 categorization (codes F20, F21, and F25) [12]. Crucially, none of the participants had been treated before the EEG was recorded. Over the course of a minute, each EEG sample was collected at a sampling rate of 128 Hz, yielding 7680 data points per channel. 16 electrodes spread over five different brain regions—frontal (F), central (C), parietal (P), temporal (T), and occipital (O)—were used to record the EEG data.

F7, F3, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, O1, and O2 were the precise electrode placements. The signals were denoised to remove artifacts before being added to the dataset. The data is organized as a 16 × 7680 matrix for each participant.

2.1.1 Schizophrenia EEG Datasets-2 (Dataset 2)

The second dataset came from research done at the Polish Institute of Psychiatry and Neurology in Warsaw. It contains EEG recordings from 28 persons in total, including 14 patients with paranoid schizophrenia (SCH) (ICD-10 code F20.0) and 14 age-and gender-matched healthy control subjects (CS). Before the EEG recordings, the patients had completed a minimum of seven days of drug washout. Each participant provided written informed consent, and the Institute's Ethics Committee approved the study. The typical worldwide 10–20 system with 19 electrodes (Fp1, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, O1, O2) was used to capture EEG data during a 15-minute eyes-closed resting-state session at a sampling frequency of 250 Hz. At FCz, the reference electrode was positioned.

2.2. EEG Pre-processing and Segmentation

We carefully clean the EEG data to guarantee accuracy and eliminate unnecessary signals during the pre-processing phase. First, 10-second non-overlapping windows are created from Datasets 1 (16 channels, 128 Hz) and 2 (19 channels, 250 Hz). Each channel is then subjected to a second-order Butterworth band-pass filter (0.5–45 Hz) to eliminate high-frequency noise and low-frequency drifts. Each subject underwent separate filtering and segmentation, and the processed segments are stored for later examination.

2.3. Featured Image Generation based on EEG Connectivity

Three steps are involved in the development of the EEG connectivity-based featured image: calculating the connectivity feature, creating a NxN connectivity matrix, and creating the connectivity-based featured image.

Seven connectivity features—magnitude square coherence (MSC), cross-power spectral density (CPSD), correlation coefficient (PC), covariance (Cov), cohentropy coefficient (CE-Coef), correntropy coefficient (RE-Coef), and phase locking value (PLV)—are computed in this study using various combinations of EEG channel pairs. While CPSD examines cross-correlation in time series for covariance distribution across frequencies (Li et al., 2020) , MSC calculates the relationship between two brain signal frequencies to forecast complicated signals using linear models (Malekpour et al., 2018). By quantifying linear correlation between data, PC uses the covariance matrix to reveal changes in brain activity (Dauwels et al., 2010). By normalizing centered cross-correntropy via mean subtraction and standard deviation division, the RE-Coef finds higher-order statistical or nonlinear correlations. Furthermore, in the frequency domain, the CE-Coef functions as a nonlinear coherence function extension (Gunduz, and Principe, 2009; Cura et al., 2023). Additionally, the synchronization of two signals' phases over time is reflected in the PLV, a connection metric. When phase discrepancies are stable, a PLV value close to one denotes good synchronization, whereas a number near 0 suggests independence and random phase variations (Adams et al., 2020).

The seven connectivity-based parameters described above are computed for every pair of EEG channels in the two schizophrenia datasets (Dataset 1 and Dataset 2). The calculated features are then normalized using the maximum-minimum normalization method. For Dataset 1, the normalized connectivity feature values derived from the subject's 16 EEG channel pairings are organized in a 16x16 connectivity matrix. Similarly, for Dataset 2, normalized connectivity feature values from the subject's 19 EEG channel pairings are organized in a 19x19

connectivity matrix. The connectivity matrix is then converted to a 224x224 resolution using nearest neighbor interpolation to preserve the relative proportions of the data points, offer consistent formatting, and improve visual clarity. Finally, the connectivity data is visualized as 224x224 pixel featured images using a "jet" colormap. These images are stored in PNG format and arranged into folders based on feature types and class labels (SCH or SC). Across the two datasets, the total image count for each feature type generated is (i) for Dataset 1: 234 CS images and 270 SCH images, and (ii) for Dataset 2: 1,299 CS images and 1,579 SCH images. All processes are carried out using MATLAB 2025a. Figure 2.2 (b,e) and (c,f) provide examples of images for a control participant and an SCH patient. MSC is used to demonstrate great coherence in red and low coherence in dark blue.

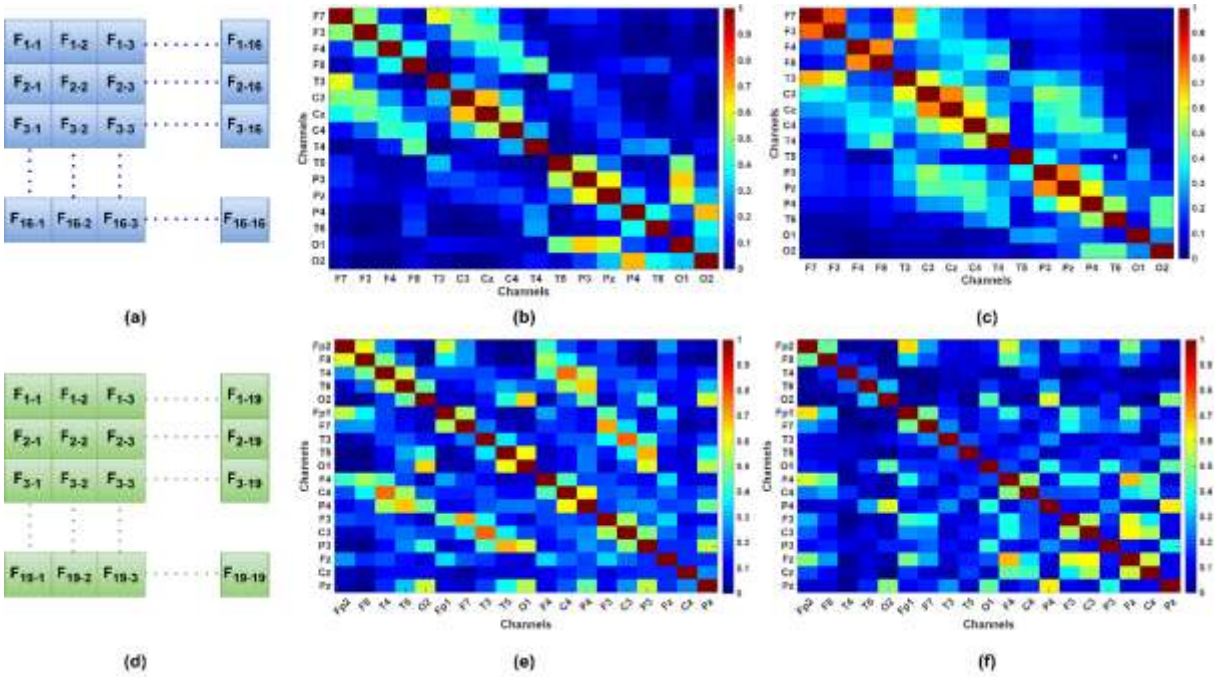


Figure 2.2. Featured image generation steps for MSC feature: (a) Brain connectivity matrix, connectivity based featured image of (b) CS (c) SCH of Dataset1; (d) Brain connectivity matrix, connectivity-based featured image of (e) CS, (f) SCH of Dataset2.

2.4 CNN-Based Classification Process

CNN-based models frequently outperform conventional hand-crafted features in classification tasks due to their great effectiveness. They are a very attractive option for the feature extraction phase of a classification pipeline due to their exceptional performance. We use a number of well-known deep CNN architectures in this study, which are well-known in artificial intelligence (AI) for their unique categorization skills. Four pre-trained CNN models—ResNet18, ResNet50, DenseNet201, and ShuffleNet—are used in this work to categorize connectivity-based featured images of SCH and CS. ResNet18 and ResNet50 are two well-known ResNet architectures. Faster training without compromising performance is the goal of ResNet18. It has an FC layer, two pooling layers, five residual blocks, and a 7x7 convolutional layer. ResNet50 is a 50-layer residual CNN that uses shortcut connections to address the backpropagation vanishing gradient issue (Shaheema, and Muppalaneni, 2025). A CNN with 201 layers, DenseNet201 is distinguished by dense connection, which enables each layer to be directly connected to every layer that came before it inside the same dense block. By using fewer parameters than conventional CNNs, this architecture ensures parameter efficiency, encourages feature reuse, and reduces the vanishing gradient issue. The design consists of

transition layers that incorporate batch normalization, 1x1 convolution for feature map reduction, and 2x2 average pooling for down-sampling, as well as dense blocks that apply the dense connectivity pattern (Yu, et al., 2019). ShuffleNet is an effective CNN that aims to minimize computational expenses while achieving high accuracy on mobile devices with low processing capacity. It makes use of two major architectural innovations: the channel shuffle operation, which permits information flow across groups to improve feature capture, and pointwise group convolution (GConv), which substitutes distinct group convolutions for conventional convolutions to reduce complexity. When compared to lightweight designs, ShuffleNet performs better, providing greater accuracy with less computational complexity (Fang, et al., 2022).

2.5 Performance Evaluation

To evaluate CNN's performance, the connectivity-based featured image datasets are divided into three subsets: training (70%), validation (15%), and testing (15%). Several evaluation criteria, such as accuracy (ACC), sensitivity (SEN), specificity (SPE), precision (PRE), and the Area Under the Receiver Operating Characteristic Curve (AUC-ROC), are employed to assess the performance of the trained CNN models.

$$SEN = \frac{TP}{TP + FN}$$
$$SPE = \frac{TN}{TN + FP}$$
$$PRE = \frac{TP}{TP + FP} \quad (1)$$
$$ACC = \frac{TP + TN}{TP + TN + FP + FN}$$

These metrics are obtained from the four components of the confusion matrix: True Positive (TP): Samples of schizophrenia that are correctly classified. Correctly identified control samples are known as True Negatives (TN). False Positive (FP): Inaccurate diagnosis of schizophrenia in control samples. False Negative (FN): Samples with schizophrenia that are mistakenly categorized as controls (Cura et al., 2023).

3. RESULTS AND DISCUSSION

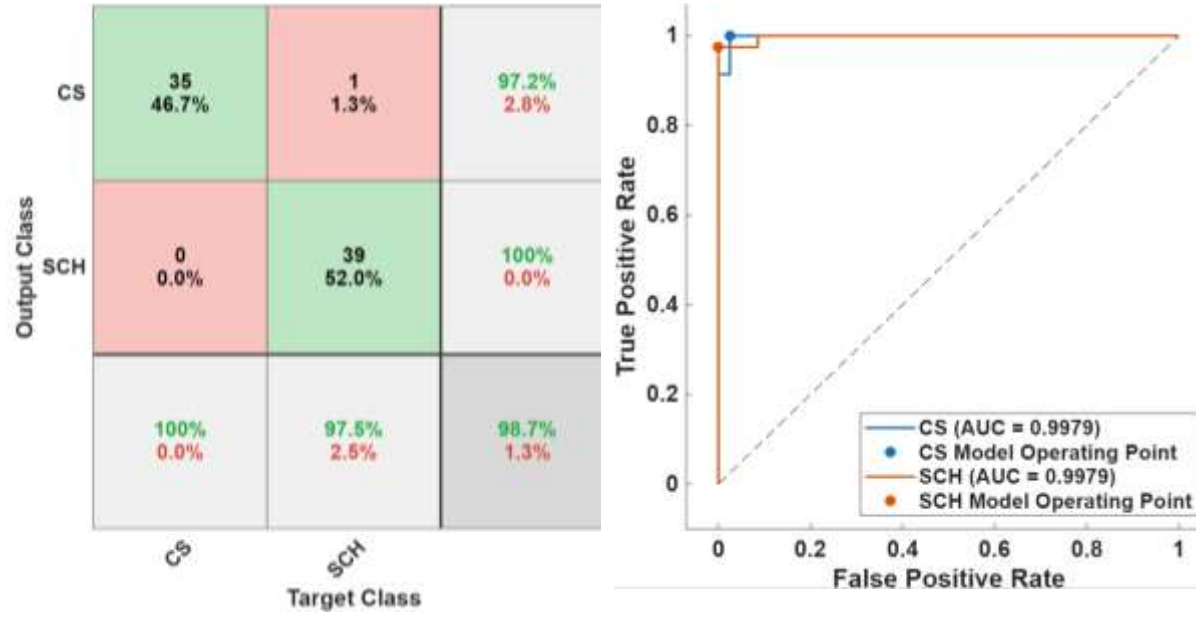
In this work, we use CNN and connectivity-based featured pictures to propose a classification method for CS and SCH patients based on their EEG signals. Seven different connectivity features—MSC, CPSD, PC, Cov, PLV, RE_Coef, and CE_Coef—are first calculated as part of our techniques. The RGB images that serve as the connectivity-based featured images are created from these computed features. To take advantage of CNN models' shown ability to distinguish SCH from CS, these connectivity-based featured images are fed into four different CNN models (ResNet18, ResNet50, DenseNet201, and ShuffleNet).

Using a variety of connectivity-based featured images (such as MSC, CPSD, PC, Covv, RE_Coef, CE_Coef, and PLV), Table 1 provides a thorough performance evaluation of four different CNN architectures—ResNet18, ResNet50, DenseNet201, and ShuffleNet—on the classification problem for Dataset 1. Perfect validation scores (ACC: 100%, SEN: 100%, SPE: 100%, PRE: 100%) and near-perfect test scores (ACC: 98.70%, SEN: 97.50%, SPE: 100%, PRE: 100%) are obtained by the ShuffleNet architecture with the RE_Coef feature set. With no false positives, the model exhibits outstanding generalization. While ResNet18 + RE_Coef and ResNet50 + MSC exhibit strong test ACC (94.70% and 98.70%, respectively), ResNet18

+ MSC also records perfect test results, raising concerns about possible data leaking among classic deep models. DenseNet201, on the other hand, performs poorly with a maximum test ACC of 84.00% and limited sensitivity in some situations. Deeper models like ResNet50 and DenseNet201 are matched or outperformed by the ShuffleNet architecture. It is the most computationally efficient choice for situations with limited resources, with a high non-perfect test ACC of 98.70%. On the test set, DenseNet201, on the other hand, frequently exhibits overfitting and insufficient feature use. Overfitting in some models is indicated by instances of notable declines in validation scores on the test set. DenseNet201 + PLV, for instance, has a validation ACC of 44.70%, which falls to 45.30% test ACC, and a validation SEN of 2.40% as opposed to 2.50% test SEN, indicating little learning. The top-performing models, ShuffleNet + RE_Coef and ResNet50 + MSC, on the other hand, show very small dips, suggesting outstanding generalization. In particular, ShuffleNet with RE_Coef achieves a test ACC of 98.70% with flawless precision and specificity, emphasizing the significance of the RE_Coef for upcoming model development.

Table 3.1. Dataset 1's classification performance using several CNN techniques and connectivity-based featured images.

		Validation				Test			
		ACC	**SEN**	**SPE**	**PRE**	**ACC**	**SEN**	**SPE**	**PRE**
ResNet18	**MSC**	97.40	97.60	97.10	97.60	***100.00***	***100.00***	***100.00***	***100.00***
	CPSD	92.10	92.70	91.40	92.70	85.30	90.00	80.00	83.70
	PC	94.70	97.60	91.40	93.00	98.70	100.00	97.10	97.60
	Cov	92.10	92.70	91.40	92.70	94.70	97.50	91.40	92.90
	RE_Coef	***100.00***	***100.00***	***100.00***	***100.00***	94.70	95.00	94.30	95.00
	CE_Coef	81.60	80.50	82.90	84.60	80.00	77.50	82.90	83.80
	PLV	44.70	0.00	97.10	0.00	45.30	0.00	97.10	0.00
ResNet50	**MSC**	98.70	100.00	97.10	97.60	98.70	97.50	100.00	100.00
	CPSD	92.10	97.60	85.70	88.90	81.30	100.00	60.00	74.10
	PC	***100.00***	***100.00***	***100.00***	***100.00***	***98.70***	***100.00***	***97.10***	***97.60***
	Covv	88.20	90.20	85.70	88.10	85.30	87.50	82.90	85.40
	RE_Coef	97.40	95.10	100.00	100.00	90.70	92.50	88.60	90.20
	CE_Coef	78.90	87.80	68.60	76.60	82.70	90.00	74.30	80.00
	PLV	55.30	100.00	2.90	54.70	53.30	100.00	0.00	53.30
DenseNet201	**MSC**	53.90	100.00	0.00	53.90	53.30	100.00	0.00	53.30
	CPSD	***82.90***	***80.50***	***85.70***	***86.80***	69.30	72.50	65.70	70.70
	PC	81.60	82.90	80.00	82.90	***84.00***	***82.50***	***85.70***	***86.80***
	Covv	75.00	92.70	54.30	70.40	81.30	90.00	71.40	78.30
	RE_Coef	69.70	48.80	94.30	90.90	57.30	32.50	85.70	72.20
	CE_Coef	42.10	7.30	82.90	33.30	44.00	5.00	88.60	33.30
	PLV	44.70	2.40	94.30	33.30	45.30	2.50	94.30	33.30
ShuffleNet	**MSC**	98.70	100.00	97.10	97.60	92.00	90.00	94.30	94.70
	CPSD	93.40	90.20	97.10	97.40	86.70	85.00	88.60	89.50
	PC	96.10	95.10	97.10	97.50	92.00	92.50	91.40	92.50
	Covv	94.70	97.60	91.40	93.00	93.30	95.00	91.40	92.70
	RE_Coef	***100.00***	***100.00***	***100.00***	***100.00***	***98.70***	***97.50***	***100.00***	***100.00***
	CE_Coef	73.70	65.90	82.90	81.80	76.00	67.50	85.70	84.40
	PLV	44.70	17.10	77.10	46.70	52.00	30.00	77.10	60.00



a) **b)**

Figure 3.1. a) Confusion Matrix, b) ROC curve, and AUC value obtained for the RE_Coef connectivity-based featured image test set of the ShuffleNet method for Dataset1

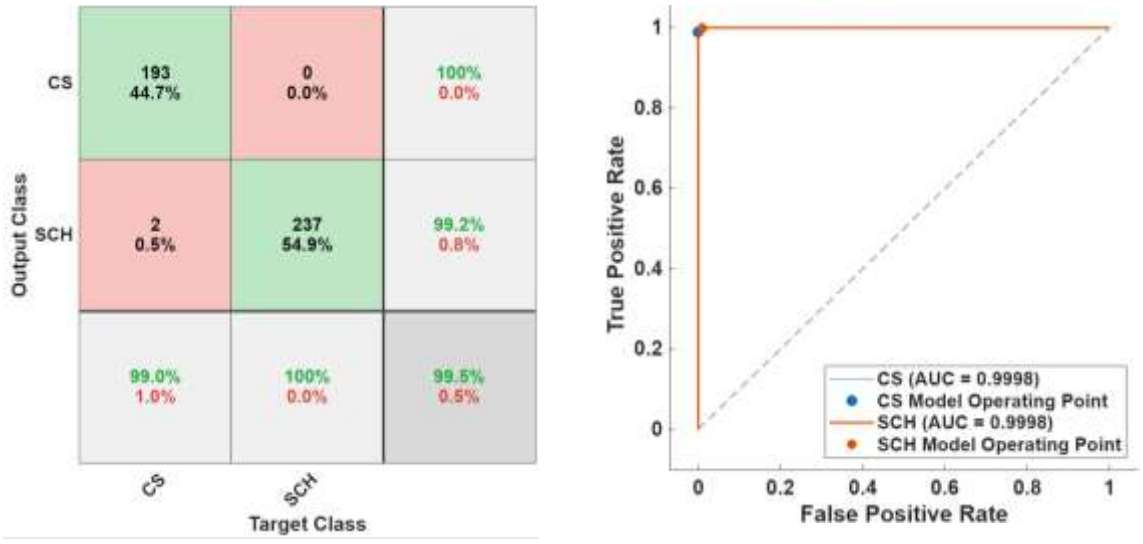
The test classification results for the ShuffleNet technique using the RE_Coef connectivity featured image set are shown in Figure 3.1, which validates the remarkable performance of the method as shown in previous tables. There are two parts to it: a) Confusion Matrix, b) Receiver Operating Characteristic (ROC) Curve with matching Area Under the Curve (AUC) value. The ShuffleNet architecture, integrated with the RE_Coef connectivity feature set, demonstrates exceptional performance in classification tasks, achieving approximately 98.7% accuracy and zero False Negatives, critical for medical diagnosis. The model's outstanding discriminatory capacity is further demonstrated by the ROC Curve and AUC of approximately 0.998, underscoring its potential as a valuable diagnostic support tool in clinical settings.

Table 3.2 presents the performance of four deep learning architectures on Dataset 2, with an emphasis on the Validation and Test set metrics to identify the optimal generalization capabilities. Both ResNet18 and ResNet50 perform well, but ResNet50 performs particularly well with the MSC and PC, obtaining test ACC of 99.50%, SEN of 100.00%, and SPE of 99.00%. With an ACC of 100.00% on validation and 97.70% on test, ShuffleNet with the RE_Coef likewise performs competitively. On the other hand, DenseNet201 shows a considerable drop in performance with some features, especially PLV, where it records a test ACC of 54.90% and SPE of 0.00%. Although ResNet50 achieves slightly higher peak metrics, ShuffleNet demonstrates greater efficiency and robust performance, especially with the PC and Re_Coef.

Table 3.2. Dataset 2's classification performance using several CNN techniques and connectivity-based featured images.

		Validation				Test			
		ACC	**SEN**	**SPE**	**PRE**	**ACC**	**SEN**	**SPE**	**PRE**
ResNet18	**MSC**	99.50	99.20	100.00	100.00	98.60	97.90	99.50	99.60
	CPSD	97.00	98.30	95.40	96.30	97.50	99.60	94.90	95.90
	PC	***99.80***	***100.00***	***99.50***	***99.60***	***99.50***	***99.60***	***99.50***	***99.60***
	Cov	98.10	100.00	95.90	96.70	96.10	97.00	94.90	95.80
	RE_Coef	99.30	99.20	99.50	99.60	97.50	96.60	98.50	98.70
	CE_Coef	91.40	92.80	89.70	91.70	88.70	89.00	88.20	90.20
	PLV	73.60	78.10	68.20	74.90	75.20	76.80	73.30	77.80
ResNet50	**MSC**	***98.60***	***99.20***	***97.90***	***98.30***	***99.50***	***100.00***	***99.00***	***99.20***
	CPSD	96.50	97.90	94.90	95.90	97.00	99.20	94.40	95.50
	PC	***99.50***	***99.60***	***99.50***	***99.60***	***99.50***	***100.00***	***99.00***	***99.20***
	Covv	98.40	99.20	97.40	97.90	95.10	97.00	92.80	94.30
	RE_Coef	98.60	99.60	97.40	97.90	98.60	99.60	97.40	97.90
	CE_Coef	92.10	94.10	89.70	91.80	88.70	93.20	83.10	87.00
	PLV	74.80	89.50	56.90	71.60	76.90	86.50	65.10	75.10
DenseNet201	**MSC**	***99.10***	***99.20***	***99.00***	***99.20***	***98.60***	***98.30***	***99.00***	***99.10***
	CPSD	97.00	96.60	97.40	97.90	96.50	97.00	95.90	96.60
	PC	99.50	99.60	99.50	99.60	98.10	98.70	97.40	97.90
	Covv	89.60	100.00	76.90	84.00	88.20	99.60	74.40	82.50
	RE_Coef	97.00	95.80	98.50	98.70	97.20	96.60	97.90	98.30
	CE_Coef	83.80	75.90	93.30	93.30	80.10	70.90	91.30	90.80
	PLV	54.90	100.00	0.00	54.90	54.90	100.00	0.00	54.90
ShuffleNet	**MSC**	98.60	99.20	97.90	98.30	98.80	99.20	98.50	98.70
	CPSD	98.80	99.20	98.50	98.70	98.80	100.00	97.40	97.90
	PC	100.00	100.00	100.00	100.00	97.70	97.90	97.40	97.90
	Covv	98.60	100.00	96.90	97.50	96.30	97.00	95.40	96.20
	RE_Coef	***99.30***	***100.00***	***98.50***	***98.80***	***99.50***	***100.00***	***99.00***	***99.20***
	CE_Coef	90.00	90.70	89.20	91.10	86.80	89.50	83.60	86.90
	PLV	70.40	84.80	52.80	68.60	72.50	82.70	60.00	71.50

Its remarkable ability to detect affirmative classes is demonstrated by its flawless SEN of 100% on the test set using Re_Coef and its perfect validation ACC of 100% with PC. It also achieves a test ACC of 99.50% with Re_Coef, making it a leading rival in terms of total performance. The supremacy of ShuffleNet as a small and effective neural network specialization for mobile and low-resource contexts is supported by its architecture. In comparison to ResNet50, which has a more complicated architecture, it drastically lowers computational cost and model size by using methods like group convolutions and channel shuffling. ShuffleNet has the best performance-to-cost ratio with classification metrics of 99.50% accuracy and 100.00% sensitivity. Its applicability for real-world high-performance applications is demonstrated by its ability to reach peak accuracy comparable to bigger models while maintaining lower latency, power consumption, and memory footprint.



a) **b)**

Figure 3.2. a) Confusion Matrix, b) ROC curve, and AUC value obtained for the RE_Coef connectivity-based featured image test set of the ShuffleNet method for Dataset2

The test classification outcomes of the ShuffleNet method using the RE_Coef connectivity-based featured image set on Dataset 2 are shown in Figure 3.2. A ROC curve with the associated AUC value and a confusion matrix make up the figure. The model exhibits perfect ACC and SEN (100.0%). The error rate is 0.5% because there are only two false positives. The ShuffleNet design with the RE_Coef connectivity-based featured image set on Dataset 2 performs exceptionally well, as shown in these figures, with an AUC of 0.9998 and SEN of 100.0%, showing great diagnostic confidence with little false alarms. Its 99.5% total accuracy ranks it among the best for jobs involving medical classification.

4. CONCLUSION

The study effectively suggested a unique classification technique based on connectivity-based featured images for differentiating between control subjects and schizophrenia patients based on their EEG signals. The methodology used the image processing power of Convolutional Neural Networks to convert NxN connectivity matrices (generated from seven distinct functional connectivity parameters, such as RE_Coef and MSC) into images.

ShuffleNet with the RE_Coef feature outperformed the other four pre-trained CNN architectures (ResNet18, ResNet50, DenseNet201, and ShuffleNet) on two publicly available datasets. It obtained a near-perfect AUC of roughly 0.998, 100.00% sensitivity, and test accuracy of 98.70% and 99.50%. With relatively few false negatives, the model showed exceptional discriminatory strength, particularly on Dataset 2. ShuffleNet demonstrated its efficacy in low-resource environments by outperforming deeper models such as ResNet50 and DenseNet201. While DenseNet201 shows overfitting, the RE_Coef function is essential for success. Overall, this study highlights the value of ShuffleNet and RE_Coef in the diagnosis of schizophrenia and promotes the use of EEG connectivity patterns in Transfer Learning-based CNNs.

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FUNGUS, BAKTERİ, VİRÜS VE NEMATOD BİTKİ PATOJENLERİNİN SÜRDÜRÜLEBİLİR VE HASSAS KONTROLÜ İÇİN CRISPR TABANLI GENOM DÜZENLEME STRATEJİLERİ

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ÖZET

Funguslar, bakteriler, virüsler ve nematodlar gibi bitki patojenleri, küresel ürün verimliliğini ve gıda güvenliğini tehdit etmektedir. Geleneksel yönetim stratejileri, patojenlerin evrimi, çevresel kaygılar ve yavaş üreme döngüleri nedeniyle sıklıkla sınırlamalarla karşılaşmaktadır. CRISPR/Cas genom düzenleme teknolojisi, patojen kontrolü için hassas ve sürdürülebilir bir alternatif sunmaktadır. Cas9 gibi yaygın olarak kullanılan nükleazlar, Cas12a, Cas13, baz düzenleyiciler ve prime düzenleyiciler ile birlikte, konakçı veya patojen genomlarının ve transkriptomlarının hedefe yönelik modifikasyonunu mümkün kılar. RNA'yı hedefleyen varyantlar, viral patojenlerle geçici olarak etkileşime girerek transgenik olmayan hastalık kontrolü sağlar. CRISPR/Cas uygulamaları, fonksiyonel gen karakterizasyonunu, dayanıklı direnç mühendisliğini ve omik, HIGS ve nanopartikül aracılı teslimat ile entegrasyonu destekler. Temel zorluklar arasında dağıtım verimliliği, hedef dışı etkiler, düzenlemeler ve kamuoyu algısı bulunmaktadır. Gelecekteki yönelimler arasında çoklu düzenleme, AI destekli hedef tasarımı ve sahada kullanıma hazır dağıtım bulunmaktadır. Genel olarak, CRISPR/Cas, dayanıklı çeşitler geliştirmek ve sürdürülebilir tarımı ilerletmek için büyük bir potansiyele sahiptir.

Anahtar Kelimeler: CRISPR/Cas Genom Düzenleme, Bitki Patojen Direnci, Fungus, Bakteriyel ve Viral Hastalıklar, Duyarlılık Geni/Genleri Düzenleme, Sürdürülebilir Ürün Koruma

CRISPR-BASED GENOME EDITING STRATEGIES FOR SUSTAINABLE AND PRECISE CONTROL OF FUNGAL, BACTERIAL, VIRAL, AND NEMATODE PLANT PATHOGENS

ABSTRACT

Plant pathogens including fungi, bacteria, viruses, and nematodes threaten global crop productivity and food security. Conventional management strategies often face limitations due to pathogen evolution, environmental concerns, and slow breeding cycles. CRISPR/Cas genome-editing technology offers a precise and sustainable alternative for pathogen control. Widely used nucleases like Cas9, along with Cas12a, Cas13, base editors, and prime editors, enable targeted modification of host or pathogen genomes and transcriptomes. RNA-targeting variants allow transient interference with viral pathogens, providing non-transgenic disease control. CRISPR/Cas applications support functional gene characterization, engineering durable resistance, and integrating with omics, HIGS, and nanoparticle-mediated delivery. Key challenges include delivery efficiency, off-target effects, regulations, and public perception. Future directions involve multiplex editing, AI-assisted target design, and field-ready deployment. Overall, CRISPR/Cas holds great potential to develop resilient crops and advance sustainable agriculture.

Keywords: CRISPR/Cas Genome Editing, Plant Pathogen Resistance, Fungal, Bacterial, and Viral Diseases, Susceptibility Gene(s) Editing, Sustainable Crop Protection

1. INTRODUCTION

Plant pathogens including fungi, bacteria, viruses, and nematodes—pose major threats to global agriculture, causing severe yield losses and compromising food security. Conventional strategies like chemical pesticides and traditional breeding face limitations due to pathogen evolution, environmental concerns, and long development times (Ali et al., 2024; Mubeen et al., 2024). Genome-editing technologies, particularly CRISPR/Cas, offer a precise and efficient alternative for developing disease-resistant crops (Wang et al., 2020). CRISPR/Cas, derived from prokaryotic adaptive immunity, enables targeted DNA and RNA modifications using simple single-guide RNAs (sgRNAs) (Wang and Doudna, 2023). It can enhance plant resistance by editing host susceptibility (S) genes, boosting resistance (R) gene expression, or directly targeting pathogen genomes (Scheben et al., 2017). Applications include conferring resistance to fungal pathogens such as *Magnaporthe oryzae* in rice, *Zymoseptoria tritici* in wheat, and *Botrytis cinerea* in tomato, as well as degrading viral RNA genomes with CRISPR/Cas13 to combat potyviruses and geminiviruses (Islam et al., 2022). Beyond crop protection, CRISPR facilitates functional analysis of host and pathogen genes, revealing mechanisms of susceptibility, immunity, and resistance (Park et al., 2024). Integration with omics and systems biology approaches—genomics, transcriptomics, metabolomics provides comprehensive insights into plant defense networks and pathogen adaptation (Borah et al., 2024). Challenges remain in field applications, including off-target effects, delivery efficiency, regulatory hurdles, and public acceptance, as well as potential pathogen adaptation to CRISPR interventions (Hajiahmadi et al., 2019). Multiplex editing and combination with conventional breeding or biotechnological strategies can address these issues. Overall, CRISPR/Cas represents a transformative tool for sustainable agriculture, enabling rapid development of resilient crops, reducing reliance on chemical inputs, and offering durable, broad-spectrum pathogen resistance. Integrating CRISPR with AI, multi-omics, and complementary technologies promises to further enhance crop protection and productivity in the 21st century.

2. OVERVIEW OF CRISPR/CAS SYSTEMS

The CRISPR/Cas system, originally discovered as an adaptive immune mechanism in bacteria and archaea, has become a powerful tool for precise genome editing in plants. It functions through small CRISPR RNAs (crRNAs) that guide Cas nucleases to complementary DNA or RNA sequences, enabling targeted cleavage (Sorek et al., 2013). Among the many variants, Cas9 is the most widely used in plants, relying on a single-guide RNA (sgRNA) to introduce double-strand breaks at specific genomic loci. This break is then repaired by cellular mechanisms such as non-homologous end joining (NHEJ) or homology-directed repair (HDR), leading to insertions, deletions, or precise sequence modifications. Beyond Cas9, new variants like Cas12a (Cpf1), Cas13, and Cas14 expand the editing toolbox. Cas12a recognizes different protospacer adjacent motif (PAM) sites and creates staggered cuts, while Cas13 specifically targets RNA, opening avenues for transient control of pathogens without permanent genome modification (Yang et al., 2020). Prime editing and base editing further enhance precision by enabling nucleotide substitutions without double-strand breaks. These advancements highlight the versatility of CRISPR/Cas platforms in tailoring plant genomes for improved pathogen resistance (Liu et al., 2022).

3. APPLICATIONS IN PLANT PATHOGEN RESISTANCE

The application of CRISPR technology in crop protection has transformed how researchers and breeders approach plant disease management. Unlike traditional breeding, which relies on naturally occurring alleles of resistance (R) genes, CRISPR allows precise modification of host genomes to either enhance natural resistance or disrupt susceptibility (S) genes that pathogens

exploit (Zaidi et al., 2018). This strategy provides a faster, more targeted pathway to develop resistant cultivars that can withstand diverse classes of pathogens, including fungi, bacteria, viruses, and nematodes. Fungal, bacterial, viral, and nematode pathogens pose major threats to global agriculture, causing significant yield losses. Traditional control strategies, including fungicides, bactericides, and conventional breeding, are limited by environmental concerns, pathogen evolution, and slow development cycles. CRISPR/Cas genome-editing offers precise, efficient, and durable alternatives for crop protection. Fungal pathogens: Targeting host susceptibility (S) genes, such as the MLO family in wheat and barley or OsERF922 in rice, confers broad-spectrum resistance to powdery mildew and blast disease (Banerjee, 2025; Wang et al., 2016). Multiplex editing of multiple S genes enhances resistance durability, while direct targeting of fungal genomes is being explored to silence pathogenicity genes (Zhang et al., 2021). Bacterial pathogens: CRISPR/Cas9 editing of host S genes, such as OsSWEET promoters in rice, prevents bacterial effectors from hijacking host systems, conferring resistance to bacterial blight while maintaining growth (Blondel et al., 2016; Pacheco et al., 2018). CRISPR can also serve as a programmable antimicrobial, selectively eliminating pathogenic bacteria without affecting beneficial microbiota (Palacios et al., 2021). Viral pathogens: CRISPR/Cas9 targets DNA viruses like geminiviruses, suppressing replication and disease symptoms, while RNA-targeting Cas13 degrades RNA viral genomes, offering broad-spectrum protection against potyviruses and cucumber mosaic virus (Ali et al., 2024; Loriato et al., 2020). Multiplexed gRNAs against conserved viral regions reduce the risk of escape mutants (Roy et al., 2019). Nematodes: CRISPR-mediated disruption of host S genes or enhancement of immune receptors reduces nematode infection and gall formation (Dutta et al., 2023). Editing host factors involved in vector recognition can also limit transmission of insect-borne viruses (Huang et al., 2023).

4. CHALLENGES AND LIMITATIONS

CRISPR-based plant pathogen control holds great promise, but several technical, biological, regulatory, and socio-economic challenges must be addressed for field deployment. A major concern is off-target mutations, where Cas nucleases cleave unintended genomic sites, potentially causing unwanted phenotypes or reduced resistance (Ali et al., 2024). High-fidelity Cas variants and computational tools mitigate risk but cannot fully eliminate it, especially in polyploid crops like wheat (Nadeem et al., 2020). Efficient delivery of CRISPR components remains a bottleneck. Traditional methods such as *Agrobacterium*-mediated transformation and particle bombardment are labor-intensive and species-specific, while many crops remain recalcitrant to transformation. Alternatives like nanoparticle-mediated delivery, viral vectors, and protoplast transfection show promise but require further optimization for efficiency, stability, and scalability (Shivashakarappa et al., 2025; Levengood et al., 2024). Pathogens can evolve to overcome CRISPR-mediated resistance, similar to conventional R gene resistance. Viral escape mutants, such as in CRISPR-edited cassava targeting geminiviruses, highlight the need for multiplex editing, targeting conserved regions, and stacking edits with traditional resistance strategies (Metha et al., 2019; Sarfraz et al., 2025). Regulatory uncertainty also limits adoption. Policies differ globally, with countries like the US and Japan adopting permissive frameworks for non-transgenic edits, while the EU treats genome-edited crops as GMOs (Rozas et al., 2022). Harmonized, science-based regulations are needed for global deployment and trade (Brookes and Smyth, 2024). Finally, complex disease resistance traits governed by multiple genes remain challenging. Multiplex editing in polyploids and precise homology-directed repair (HDR) are technically difficult, limiting the introduction of complex resistance alleles. New tools such as prime editors may improve the efficiency of multi-gene editing and enable more durable disease resistance (May et al., 2023; Barka and Lee, 2022).

5. CONCLUSION

CRISPR/Cas technologies have emerged as a revolutionary tool in plant pathogen management, offering unprecedented precision, efficiency, and versatility. By enabling targeted editing of host susceptibility and resistance genes, as well as direct interference with pathogen genomes, CRISPR provides a powerful alternative to conventional breeding and chemical control methods. The diversity of CRISPR systems including Cas9, Cas12a, Cas13, base editors, and prime editors allows tailored approaches for DNA and RNA pathogens, facilitating broad-spectrum and durable resistance across a wide range of crops. Case studies in cereals, horticultural crops, and model plants demonstrate the practical potential of CRISPR to improve pathogen resistance while maintaining plant growth and yield. Integration with complementary technologies, such as omics-based target discovery, host-induced gene silencing, and advanced delivery systems, further enhances the efficacy and applicability of genome editing. Despite its promise, challenges remain, including off-target effects, delivery limitations, regulatory hurdles, and public acceptance. Addressing these concerns through improved Cas variants, multiplex editing strategies, AI-assisted design, and transparent stakeholder engagement will be critical for successful implementation. Overall, CRISPR/Cas-based approaches represent a transformative opportunity to develop resilient crops, reduce dependence on chemical inputs, and contribute to sustainable agriculture and global food security.

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BİTKİ BÜYÜMESİNİN SÜRDÜRÜLEBİLİR ŞEKİLDE GELİŞTİRİLMESİ İÇİN BİYOJENİK NANOPARTİKÜLLER: MEKANİZMALAR, UYGULAMALAR VE GELECEK BEKLENTİLERİ

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ÖZET

Bitkiler, funguslar ve miroorganizmalar tarafından üretilen biyojenik nanopartiküller (NP'ler), bitki büyümesini ve verimliliğini artırmak için çevre dostu, biyolojik olarak parçalanabilir ve biyouyumlu çözümler sunar. Bu NP'ler besin alımını artırır, fitohormonları uyarır, antioksidan savunmayı güçlendirir ve kuraklık, tuzluluk ve ağır metallere karşı toleransı artırır. Ag, ZnO, CuO ve TiO_2 gibi yaygın biyojenik NP'ler çimlenme, kök ve sürgün büyümesi, klorofil içeriği, biyokütle ve verimi önemli ölçüde iyileştirir. Tohum hazırlama, yaprak spreyi ve toprak ıslahı gibi uygulama yöntemleri hedefe yönelik dağıtımı mümkün kılarken, hassas tarımla entegrasyon verimliliği artırır. Biyojenik NP'ler ayrıca besin döngüsünü ve bitki sağlığını desteklemek için faydalı mikroplarla sinerjik olarak çalışır. Doz optimizasyonu ve çevresel değerlendirme yoluyla güvenli kullanımın sağlanması hala çok önemlidir. Genel olarak, biyojenik NP'ler bitki büyümesini teşvik etmek ve stresi azaltmak için sürdürülebilir araçlar olarak güçlü bir potansiyel göstermektedir, ancak saha doğrulaması, uygulama optimizasyonu ve akıllı tarım teknolojileriyle entegrasyon konusunda gelecekte daha fazla çalışma yapılması gerekmektedir.

Anahtar Kelimeler: Biyojenik Nanopartiküller, Bitki Büyümesini Teşvik Etme, Stres Toleransı, Nano Gübreler, Sürdürülebilir Tarım

BIOGENIC NANOPARTICLES FOR SUSTAINABLE ENHANCEMENT OF PLANT GROWTH: MECHANISMS, APPLICATIONS, AND FUTURE PROSPECTS

ABSTRACT

Biogenic nanoparticles (NPs) produced by plants, fungi, and microbes offer eco-friendly, biodegradable, and biocompatible solutions for improving plant growth and productivity. These NPs enhance nutrient uptake, stimulate phytohormones, strengthen antioxidant defenses, and boost tolerance to drought, salinity, and heavy metals. Common biogenic NPs such as Ag, ZnO, CuO, and TiO_2 significantly improve germination, root and shoot growth, chlorophyll content, biomass, and yield. Application methods—including seed priming, foliar sprays, and soil amendments enable targeted delivery, while integration with precision agriculture increases efficiency. Biogenic NPs also work synergistically with beneficial microbes to support nutrient cycling and plant health. Ensuring safe use through dose optimization and environmental assessment remains essential. Overall, biogenic NPs show strong potential as sustainable tools for plant growth promotion and stress mitigation, with future work needed on field validation, application optimization, and integration with smart farming technologies.

Keywords: Biogenic Nanoparticles, Plant Growth Promotion, Stress Tolerance, Nano-Fertilizers, Sustainable Agriculture

1. INTRODUCTION

Agriculture is increasingly threatened by soil nutrient depletion, environmental stresses, and excessive use of chemical fertilizers and pesticides, all of which reduce crop productivity and long-term sustainability. As a result, innovative solutions are needed to enhance plant growth while minimizing environmental impact. Nanotechnology offers one such approach, with biogenic NPs emerging as particularly promising due to their eco-friendly synthesis and multifunctional roles in plants (Tolisano and Del Buono, 2023). Produced from natural sources such as plants, bacteria, fungi, and algae, biogenic NPs are safer for crops, soil microbes, and ecosystems compared to chemically synthesized NPs. Their unique physicochemical and biological properties enable them to enhance nutrient uptake, stimulate plant hormones, and improve tolerance to both abiotic and biotic stresses (Bhati, 2023). They also interact positively with soil microorganisms, supporting microbial activity and overall soil health. Biogenic NPs function as nano-fertilizers, bio-stimulants, and stress mitigators, making them attractive tools for precision and sustainable agriculture. Interest in their use has expanded rapidly in recent years (Mishra, 2024), driven by their potential to reduce dependence on synthetic fertilizers and improve crop performance in a targeted manner. Ongoing research focuses on clarifying their mechanisms of action and optimizing their safe application in field conditions (Ali et al., 2024).

Despite their promise, key challenges remain, including dose optimization, phytotoxicity assessment, environmental safety, and scalable production (Deshmukh et al., 2023). Addressing these issues requires interdisciplinary collaboration across nanotechnology, plant physiology, soil science, and environmental research. Future directions include integrating biogenic NPs with smart delivery systems, precision agriculture tools, and data-driven approaches. Overall, biogenic NPs represent a rapidly advancing and sustainable strategy to enhance plant growth, nutrient efficiency, and stress resilience while minimizing environmental risks.

2. SYNTHESIS OF BIOGENIC NPS

2.1 Plant-Mediated Synthesis

Plants are rich in biomolecules such as flavonoids, phenolics, terpenoids, and proteins that can reduce metal ions to form NPs. Extracts from leaves, roots, fruits, and seeds have been widely used to synthesize silver, zinc oxide, copper oxide, and titanium dioxide NPs (Shyam et al., 2021). In these extracts, reducing agents convert metal salts into nanoscale particles, while natural capping agents stabilize them and prevent aggregation. This green synthesis is simple, cost-effective, and environmentally safe, with particle size and shape easily controlled by adjusting extract concentration, temperature, pH, and reaction time. Plant-mediated NPs are highly biocompatible with plants and soil microbes (Khan et al., 2025). For example, leaf extracts of *Azadirachta indica* and *Ocimum sanctum* have been used to produce silver and zinc oxide NPs that enhance seed germination and early seedling growth in wheat and tomato (Giri et al., 2023; Ansari et al., 2023). These NPs also exhibit strong antimicrobial activity, helping protect crops from pathogens. Because the process avoids toxic chemicals, it reduces environmental risks and yields biodegradable, non-toxic NPs suitable for agriculture. Advances in phytochemical analysis are helping identify the specific plant compounds responsible for nanoparticle formation (Zuhrotun et al., 2023), enabling better optimization of synthesis conditions for uniform and functionally enhanced NPs. Additionally, agricultural waste is increasingly being explored as a low-cost feedstock for NP production. Overall, plant-mediated synthesis offers an efficient, sustainable, and highly functional approach for generating biogenic NPs to support plant growth and stress tolerance.

2.2 Microbe-Mediated Synthesis

Microorganisms including bacteria, fungi, and algae can synthesize NPs through enzymatic reduction of metal ions. Fungi are especially effective producers due to their abundant extracellular enzymes and metabolites (Zhou et al., 2024), while bacterial genera such as *Bacillus* and *Pseudomonas* have been widely used to generate silver, gold, and zinc NPs. Depending on the microbial strain, growth conditions, and metal precursor concentration, NPs can be produced intra- or extracellularly with tunable size and morphology (Tsekhmistrenko et al., 2020). Algal species are also emerging as efficient NP producers, often yielding particles enriched with bioactive compounds that further enhance plant growth (Koul et al., 2021). Microbe-mediated NP synthesis is sustainable, avoids hazardous chemicals, and naturally stabilizes NPs through microbial proteins. These NPs interact synergistically with plant roots, improving nutrient uptake and stimulating growth-promoting hormones. The process is scalable under controlled conditions, making it suitable for commercial production. Additionally, microbial systems offer complementary benefits such as soil enrichment and biocontrol activity (Koskey et al., 2021). Recent work shows that fungal-derived ZnO NPs can boost chlorophyll levels and antioxidant activity in crops (Singh et al., 2024). Integrating microbial NPs with biofertilizers represents a promising strategy for sustainable and circular agriculture, utilizing low-cost microbial biomass and residues.

3. MECHANISMS OF PLANT GROWTH ENHANCEMENT

3.1 Improved Nutrient Uptake and Bioavailability

Biogenic NPs enhance plant nutrient uptake by increasing the availability and mobility of macro- and micronutrients (Semenova et al., 2024). Their high surface-area-to-volume ratio facilitates nutrient adsorption and transport, while slow release of ions from NPs like ZnO, Ag, and Cu improves root absorption and phosphorus and iron mobilization (Kachel et al., 2021). NPs can penetrate roots and leaves, interacting with transport proteins and stomata to boost nutrient assimilation (Hong et al., 2021), and they also support soil microbes in solubilizing otherwise inaccessible nutrients. Applications such as seed priming or foliar sprays improve germination, early growth, chlorophyll content, protein synthesis, and overall plant vigor, while reducing fertilizer losses and environmental contamination (Fatima et al., 2021). By activating root transporters and enhancing ion uptake under nutrient-limited conditions (Zhao et al., 2024), biogenic NPs optimize nutrient efficiency, maintain soil fertility, and act as nano-fertilizers and growth promoters, supporting sustainable agriculture.

3.2 Stimulation of Phytohormones

Nanoparticles (NPs) can modulate plant hormone levels and signaling pathways, enhancing growth and development. They influence the synthesis of auxins, cytokinins, gibberellins, and abscisic acid, promoting root elongation, lateral root formation, shoot growth, leaf expansion, chlorophyll synthesis, stem elongation, and flowering (Tripathi et al., 2022). Seed priming with NPs accelerates early development by activating hormone-related genes (Khan et al., 2023), improving nutrient allocation, stress tolerance, photosynthetic efficiency, and secondary metabolite production. Controlled NP doses optimize hormonal balance without toxicity, and integration with bio-stimulants or microbial inoculants can further enhance effects. Studies report increased biomass, leaf area, and faster germination in crops treated with biogenic NPs (Mickky, 2025), highlighting their potential as a sustainable, non-chemical strategy to boost crop growth.

3.3 Enhanced Stress Tolerance

Abiotic stresses such as drought, salinity, heavy metals, and extreme temperatures limit global crop productivity. Biogenic NPs enhance plant stress tolerance by activating antioxidant systems, including superoxide dismutase, catalase, and peroxidase, reducing oxidative damage (Shaikh et al., 2025). Zinc oxide NPs, for example, improve drought tolerance in wheat by increasing osmolyte accumulation, chlorophyll content, membrane stability, and water retention. NPs can chelate heavy metals, maintain ion homeostasis in saline soils, and trigger stress-responsive genes, boosting photosynthesis, energy metabolism, root growth, and yield (Tombuloglu et al., 2024). Their small size allows cellular-level action, and synergistic interactions with beneficial microbes further enhance resilience (Anas et al., 2025). Biogenic NPs thus function as effective nano-protectants, helping plants withstand environmental stresses.

4. APPLICATIONS OF BIOGENIC NPS IN AGRICULTURE

Biogenic NPs have versatile applications in agriculture, enhancing plant growth, productivity, and stress tolerance. Seed priming with Ag, ZnO, and CuO NPs improves germination, seedling vigor, root and shoot development, water uptake, enzyme activity, and resistance to abiotic stresses while reducing seed-borne pathogens (Kathiravan et al., 2024). Foliar sprays deliver nutrients directly through stomata, boosting chlorophyll content, photosynthesis, antioxidant activity, and drought and salinity tolerance. Soil amendments enhance nutrient availability, root growth, microbial activity, nitrogen fixation, and mycorrhizal symbiosis, while mitigating nutrient leaching and heavy metal stress. Integration with hydroponics and precision agriculture allows targeted nutrient delivery and real-time monitoring, optimizing yield and quality with minimal environmental impact (Bouarroudj et al., 2025). Combining NPs with bio-stimulants or beneficial microbes further improves nutrient use efficiency and stress resilience. Overall, biogenic NPs provide a sustainable, multifunctional, and eco-friendly approach to modern crop production.

5. SAFETY AND ENVIRONMENTAL CONSIDERATIONS

Biogenic NPs are generally safe for agriculture, but excessive concentrations can cause phytotoxicity by disrupting cellular metabolism, inducing oxidative stress, and damaging membranes. Dose optimization, particle size control, and appropriate application methods are therefore crucial. Low to moderate doses of Ag, ZnO, and CuO NPs enhance growth, whereas higher doses can inhibit germination, reduce biomass, and impair chlorophyll synthesis and root development (Wohlmuth et al., 2022). Green-synthesized NPs are more biocompatible than chemical ones, and coatings or controlled-release systems can further reduce toxicity. While NPs can interact with soil, water, and microbes, optimized applications support beneficial microbial activity, reduce chemical fertilizer use, and minimize environmental contamination (Elsilk et al., 2024). Long-term field studies, monitoring, and regulatory frameworks are essential to ensure sustainable use, addressing safe concentrations, environmental impacts, and phytotoxicity (Vilela et al., 2023). Careful application and adherence to guidelines make biogenic NPs an eco-friendly and effective tool for sustainable agriculture.

6. CONCLUSION

Biogenic NPs represent a transformative tool for sustainable agriculture. Their green synthesis using plants, fungi, and microbes ensures biocompatibility, biodegradability, and reduced environmental risks. These NPs enhance plant growth through improved nutrient uptake, stimulation of phytohormones, and activation of antioxidant defenses. They provide increased

tolerance to abiotic stresses such as drought, salinity, and heavy metals. Seed priming, foliar sprays, and soil amendments are effective methods for delivering NPs to crops. Integration with hydroponics and precision agriculture further maximizes their efficiency and sustainability. Silver, zinc oxide, copper oxide, and titanium dioxide NPs are the most widely studied and have demonstrated significant improvements in germination, biomass, yield, and quality. Safety and environmental considerations, including dose optimization, phytotoxicity assessment, and microbial impact, are essential for responsible use. Overall, biogenic NPs offer a promising strategy to enhance plant growth, resilience, and productivity in a sustainable and environmentally responsible manner. Their multifunctional role as growth promoters, nutrient enhancers, and stress mitigators positions them as a key innovation in next-generation agriculture. With continued research, optimized application strategies, and regulatory support, biogenic NPs have the potential to revolutionize sustainable crop production worldwide.

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DEMİRKÖPRÜ BARAJ GÖLÜ BALIKÇILIĞINDA AV ARACI BAZINDA BİRİM ÇABA BAŞINA DÜŞEN AV MİKTARININ (CPUE) BELİRLENMESİ

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ÖZET

Ege Bölgesi'ndeki en büyük yüzey alanına sahip ve en önemli balıkçılık sahalarından biri olan Demirköprü Baraj Gölü'nde (Manisa) ticari balıkçılığın serbest olduğu Haziran 2024-Şubat 2025 döneminde ayda 2 gün olmak üzere karaya çıkış noktalarında gözlem ve balıkçılarla anket yapılarak balıkçıların günlük av miktarları, kullandıkları av araçlarının türü (uzatma ağı, pinter, paraketa) ve miktarları tespit edilmiştir. Çalışma boyunca 349'u sadece uzatma ağı kullanan, 27'si sadece pinter kullanan, 23'ü sadece paragat kullanan, 37'si uzatma ve pinteri birlikte kullanan, 30'u uzatma ve paragatı birlikte kullanan olmak üzere toplam 466 balıkçı teknesi örneklenmiştir. Av miktarı ve çaba (uzatma ağı, pinter, paraketa miktarı) verileri kullanılarak; av sezonu ve aylar için birim çaba başına düşen av miktarı (CPUE) değerleri av aracı bazında olmak üzere uzatma ağı (kg / m / gün), pinter (kg / adet / gün) ve paragat (kg / 100 iğne / gün) için hesaplanmıştır. Av sezonu için av aracı bazında CPUE değerleri uzatma ağında 0,030 ± 0,015 kg/m/gün, pinterde 0,139 ± 0,078 kg/adet/gün ve paragat için 0,153 ± 0,075 kg/100 iğne/gündür. CPUE değerlerinin aylık karşılaştırmalarında, üç av aracında da aylar arasında istatistik olarak anlamlı farklılık tespit edilmiştir (uzatma ağı için p = 0,001; pinter için p = 0,016; paragat için p = 0,028).

Anahtar Kelimeler: Demirköprü Baraj Gölü, CPUE, uzatma ağı, pinter, paragat

DETERMINATION OF FISHING EFFORT AND CATCH PER UNIT EFFORT (CPUE) BASED ON FISHING GEAR IN DEMİRKÖPRÜ DAM LAKE FISHERY

ABSTRACT

Surveys were conducted with fishermen at landing points twice a month to determine the daily catch, the types and quantities of fishing gear (gillnets, trawls, longlines) during the period when commercial fishing season (June 2024–February 2025) at the Demirköprü Dam Lake (Manisa), which has the largest surface area and is one of the most important fishing areas in the Aegean Region. A total of 466 fishing vessels were sampled, 349 of which used only gillnets, 27 of which used only fyke nets, 23 of which used only longlines, 37 of which used both gillnets and fyke nets, and 30 of which used both gillnets and longlines. Using the catch amount and effort (gillnet, fyke net, longline amount) data, the catch per unit effort (CPUE) values for the fishing season and months were calculated on a fishing gear basis for gillnet (kg/m/day), fyke net (kg/number /day) and longline (kg/100 hooks/day). For the fishing season, the CPUE values on a gear basis were 0.030±0.015 kg/m/day for gillnets, 0.139±0.078 kg/number/day for fyke nets and 0.153±0.075 kg/100 needles/day for longlines. Statistically significant differences were found in monthly comparisons of CPUE values for all three types of fishing gear (for gillnets p=0,001; for fyke nets p=0,016; for longlines p=0,028).

Keywords: Demirköprü Dam Lake, CPUE, gillnet, fyke net, longline

GİRİŞ

Ege Bölgesi'nin en fazla yüzey alanına sahip baraj gölü olan Demirköprü Baraj Gölü'nde (Anonim, 1989; Ünal vd., 2011) yürütülen bilimsel çalışmalar ve literatür incelendiğinde; kullanılan av araçları ve hedeflenen ticari türler (Dereli ve diğ., 2018), gümüşi havuz balığının biyolojik özellikleri (Dereli ve diğ., 2021), sazan balıkçılığındaki uzatma ağlarının av verimi/seçiciliği ve sazan balıkçılığının yönetimi (Dereli ve diğ., 2022), sazan balığının büyüme modelleri (Dereli ve Bayhan, 2023) konularının ele alındığı görülmektedir.

Birim çaba başına düşen av miktarı (CPUE), temel balık stoklarının zaman içindeki göreceli bolluğu veya göreceli biyokütle eğilimlerindeki geniş eğilimlerin birinci dereceden değerlendirilmesi için sıklıkla kullanılan temel bir balıkçılık bilimi ölçüsüdür (Skalski ve diğerleri, 2005; Belhabib ve diğerleri, 2018). CPUE'nin sınırlamaları olsa da, özellikle daha ayrıntılı verilerin ve stok değerlendirmelerinin mevcut olmadığı (Stamatopoulos, 2002) ve açık veya yarı açık erişimli balıkçılığın baskın olduğu, yani kısıtlayıcı olduğu durumlarda, bir balıkçılığın uzun vadeli eğiliminin izlenmesinde faydalı olabilir (Zeller ve diğ., 2021). Bu çalışmada; Demirköprü Baraj Gölü için balıkçılık çabası ve CPUE değerlerinin av aracı bazında tespit edilmesi amaçlanmıştır.

MATERYAL VE METOT

Demirköprü Baraj Gölü'nde (Manisa) ticari balıkçılığın serbest olduğu Haziran 2024-Şubat 2025 döneminde ayda 2 gün olmak üzere karaya çıkış noktalarında gözlem ve balıkçılarla anket yapılarak balıkçıların günlük av miktarları, kullandıkları av araçlarının türü (uzatma ağı, pinter, paraketa) ve miktarları tespit edilmiştir. Uzatma ağlarının donam faktörleri, balıkçılarla görüşülerek, karaya çıkış noktalarında ağlar kontrol edilerek ve ağları yapan balıkçılarla görüşülerek tespit edilmiştir. Av miktarı ve çaba (uzatma ağı, pinter, paraketa miktarı) verileri kullanılarak; av sezonu ve aylar için birim çaba başına düşen av miktarı (CPUE) değerleri av aracı bazında olmak üzere uzatma ağı (kg/m/gün), pinter (kg/adet/ gün) ve paragat (kg/100 iğne/gün) için hesaplanmıştır.

Veriler, IBM SPSS Statistics 22.0 (IBM Corp., Armonk, New York, ABD) istatistik paket programında değerlendirilmiştir. Tanımlayıcı istatistikler olarak örneklem sayısı (n), ortalama ±standart sapma ($\bar{x} \pm ss$), %95 güven aralığı (GA), Medyan ve IQR (çeyrekler arası aralık) değerleri verilmiştir. Sayısal değişkenlere ait verilerin normal dağılımı Shapiro Wilk normallik testi ve Q-Q grafikleri ile değerlendirilmiştir. CPUE değerlerinde gruplar (aylar) arası karşılaştırmalar, normal dağılım gösteren değişkenlerde tek yönlü varyans analizi ile, normal dağılım göstermeyen değişkenlerde Kruskal-Wallis analizi ile yapıldı. Çoklu karşılaştırma testi olarak normal dağılan değişkenlerde Tukey HSD, normal dağılmayan değişkenlerde Dunn-Bonferroni testi kullanıldı. $p<0,05$ değeri istatistiksel olarak anlamlı kabul edildi.

BULGULAR

Aylık örneklemelerde 9 aylık çalışma boyunca örneklenen 466 balıkçı teknesinin 349'u sadece uzatma ağı kullanan, 27'si sadece pinter kullanan, 23'ü sadece paragat kullanan, 37'si uzatma ve pinteri birlikte kullanan, 30'u uzatma ve paragatı birlikte kullanan teknelerdir.

Uzatma ağlarında donam faktörleri ve bir posta ağ uzunluğu; 50 mm göz açıklığına sahip ağlarda 0,40 (80,8 m), 65 mm göz açıklığına sahip ağlarda 0,39 (77,7 m), 70 mm göz açıklığına sahip ağlarda 0,35 (68,9 m), 75 mm göz açıklığına sahip ağlarda 0,32 (64,3 m), 80 mm göz açıklığına sahip ağlarda 0,30 (60,3m), 85 mm göz açıklığına sahip ağlarda 0,27 (52,9 m), 90 mm göz açıklığına sahip ağlarda 0,24 (47,2 m) olarak hesaplanmıştır.

Uzatma ağı için kg/m/gün, pinter için kg/adet/gün ve paragat için kg/100 iğne/gün olarak hesaplanan aylık ve av sezonu CPUE değerlerinin tanımlayıcı istatistikleri Tablo 1'de verilmiştir. Av sezonu ortalama CPUE değerleri uzatma ağında 0,030±0,015 kg/m/gün, pinterde 0,139±0,078 kg/adet/gün ve paragat için 0,153±0,075 kg/100 iğne/gün olarak hesaplanmıştır (Tablo1).

Tablo 1: Av araçlarının (Uzatma ağı, pinter, paragat) CPUE değerlerine ilişkin tanımlayıcı istatistikleri (*n*: sayı; $\bar{x}\pm ss$: ortalama ± standart sapma; *GA*: %95 güven aralığı; A: alt sınır; Ü: üst sınır)

	Uzatma ağı (n=418) **(kg/m/gün)**		**Pinter** (n=73) **(kg/adet/gün)**		**Paragat** (n=50) **(kg/100 iğne/gün)**	
	$\bar{x}\pm ss$	*GA* (A-Ü)	$\bar{x}\pm ss$	*GA* (A-Ü)	$\bar{x}\pm ss$	*GA* (A-Ü)
Haziran 2024	0,044± 0,026	0,037-0,051	0,188± 0,0962	0,147- 0,229	0,245± 0,099	0,163-0,328
Temmuz 2024	0,029± 0,010	0,026- 0,032	0,116± 0,075	0,080 0,151	0,146± 0,089	0,082- 0,210
Ağustos 2024	0,029± 0,008	0,027-0,031	0,126± 0,026	0,107- 0,146	0,101± 0,048	0,023-0,178
Eylül 2024	0,017± 0,007	0,015-0,019	0,111± 0,031	0,071- 0,150	0,15± 0,041	0,090-0,221
Ekim 2024	0,021± 0,009	0,018-0,023	0,150± 0,014	0,022- 0,277	0,105± 0,014	0,022-0,232
Kasım 2024	0,031± 0,009	0,028- 0,035	0,128± 0,034	0,073- 0,183	0,105± 0,014	0,022- 0,232
Aralık 2024	0,030± 0,007	0,027-0,033	0,070± 0,009	0,014- 0,154	0,144± 0,021	0,122-0,166
Ocak 2025	0,030± 0,009	0,026-0,033	0,100± 0,041	0,035- 0,166	0,122± 0,064	0,055-0,189
Şubat 2025	0,034± 0,010	0,030-0,038	0,055± 0,007	0,008- 0,118	0,145± 0,024	0,124-0,165
Av sezonu	0,030± 0,015	0,028-0,031	0,139± 0,078	0,120- 0,157	0,153± 0,075	0,131-0,174

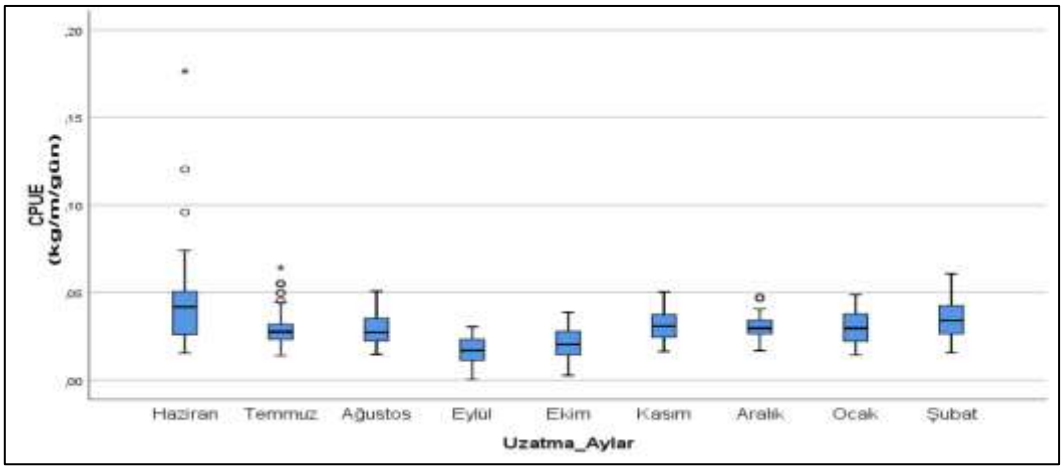
Av araçları (uzatma ağı, pinter, paragat) için tespit edilen aylık CPUE değerleri (medyan ve çeyrekler arası aralık (IQR)) Tablo 2'de, aylık kutu-bıyık (box and whisker) grafikleri ise Şekil 1, 2 ve 3'de sunulmuştur. CPUE değerlerinin aylık karşılaştırmalarında, üç av aracında da aylar arasında aylar arasında istatistik olarak anlamlı farklılık tespit edilmiştir (uzatma ağı, p=0,001; pinter, p=0,016; paragat, p=0,028) (Tablo 2).

Tablo 2: Av araçlarına göre (Uzatma ağı, pinter, paragat) aylık CPUE değerlerinin karşılaştırılması (IQR: Çeyrekler arası aralık)

	Av aracı		
	Uzatma ağı (kg/m/gün)	**Pinter (kg/adet/gün)**	**Paragat (kg/100 iğne/gün)**
	Medyan (IQR)	*Medyan (IQR)*	*Medyan (IQR)*
Haziran 2024	0,0418 [a] (0,02)	0,1822 [a] (0,14)	0,2300 [a] (0,18)
Temmuz 2024	0,0276 [b] (0,01)	0,1110 [a] (0,07)	0,1075 [a] (0,28)
Ağustos 2024	0,0273 [b] (0,01)	0,1200 [a] (0,04)	0,0975 [a] (0,11)
Eylül 2024	0,0169 [c] (0,01)	0,1067 [a] (0,09)	0,1575 [a] (0,08)
Ekim 2024	0,0205 [c] (0,01)	0,1500 [a] (0,02)	0,1050 [a] (0,02)
Kasım 2024	0,0310 [a,b] (0,01)	0,1350 [a] (0,07)	0,1050 [a] (0,02)
Aralık 2024	0,0297 [a,b] (0,01)	0,0700 [a] (0,00)	0,1475 [a] (0,04)
Ocak 2025	0,0297 [a,b] (0,02)	0,0945 [a] (0,08)	0,1050 [a] (0,13)
Şubat 2025	0,0340 [a,b] (0,02)	0,0550 [a] (0,00)	0,1375 [a] (0,04)
Kruskal-Wallis Test	$p = 0,001$	$p = 0,016$	$p = 0,028$

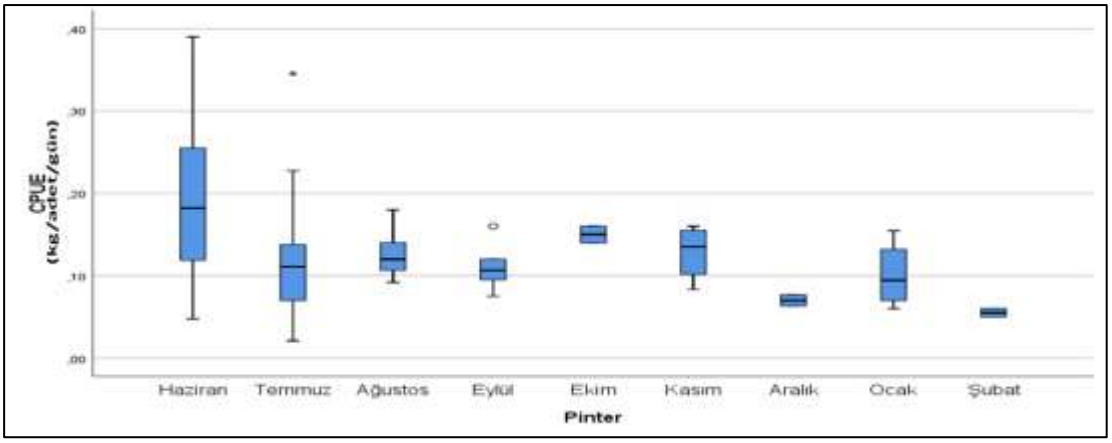
[a, b, c] üst simgeleri gruplar arası farklılığı göstermektedir. Aynı harflerin yer aldığı gruplarda fark bulunmamaktadır.

Uzatma ağında, Haziran ayındaki CPUE değerleri istatistik olarak anlamlı derecede Temmuz, Ağustos, Eylül, Ekim aylarından daha yüksektir. Eylül ve Ekim ayları değerleri diğer tüm aylardan istatistik olarak anlamlı derecede daha düşüktür ($p<0,05$) (Tablo 2 ve Şekil 1).



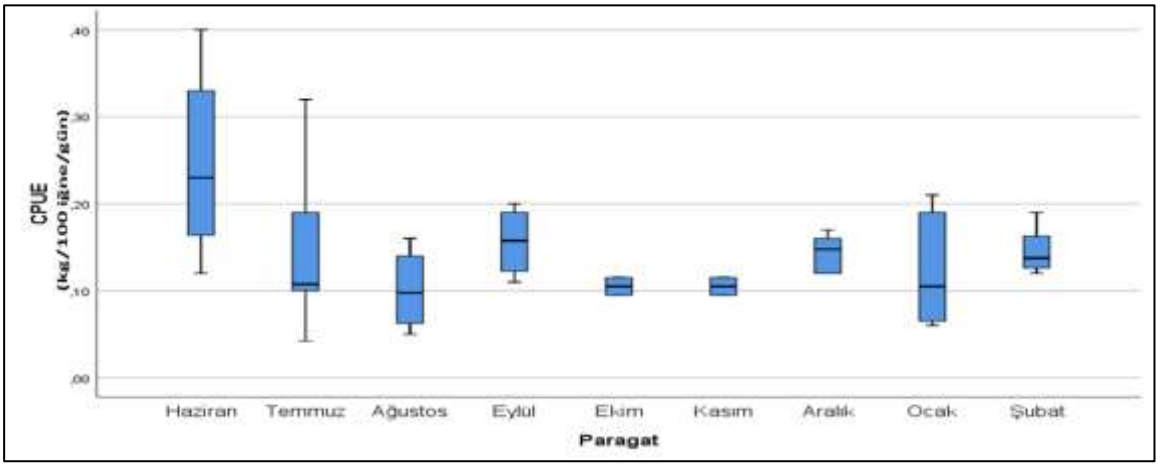
Şekil 1: Uzatma ağı CPUE değerlerinin aylık değişimi

Pinterde CPUE değerlerinin istatistik olarak anlamlı derecede fark bulunmamakla birlikte Haziran ayında en yüksek, Şubat ayında ise en düşük olduğu belirlenmiştir (Tablo 2 ve Şekil 2).



Şekil 2: Pinter CPUE değerlerinin aylık değişimi

Paragatta en yüksek CPUE değeri, istatistik olarak anlamlı derecede fark bulunmamakla birlikte Haziran ayında, en düşük ise Ağustos ayında tespit edilmiştir (Tablo 2 ve Şekil 3).



Şekil 3: Paragat CPUE değerlerinin aylık değişimi

TARTIŞMA VE SONUÇ

Demirköprü Baraj Gölü balıkçılığında uzatma ağı, pinter ve paragat av araçlarını tek başına kullanan tekneler olduğu gibi, iki av aracını (uzatma ağı ve pinter; uzatma ağı ve paragat) birlikte kullanan tekneler de bulunmaktadır. Av aracı bazında tespit edilen CPUE'larda aylık değerler arasında istatistiksel farklılık vardır. En yüksek değerler, paragat ve pinterde istatistiksel fark bulunmamakla birlikte av sezonu başında Haziran ayındadır.

Balıkçılar her üç av aracıyla da sazan ve yayın türünü hedeflemekte olup uzatma ağı balıkçılığında 65-90 mm ağ göz genişliklerindeki ağları kullanmaktadırlar. Balıkçılar, av miktarındaki düşüş nedeniyle Kasım ayından itibaren *Carassius sp.* türlerini hedefleyerek daha düşük göz genişliklerindeki uzatma ağlarını da (50 mm) kullanmaktadırlar. Bu sebeple toplam av miktarı, Kasım-Şubat döneminde *Carassius sp.* türünün av vermesiyle sezon başı değerlerine ulaşamasa da artmıştır.

Ülkemizde içsu balıkçılığında Beyşehir Gölü (Konya) (Balık, 2001), Uluabat Gölü (Bursa) (Balık ve Çubuk, 2001), Homa Lagünü (İzmir) (Acarlı ve diğ, 2009), Demirköprü Baraj Gölü

(Manisa) (Şen, 2016, Eğirdir Gölü (Isparta) (Korkmaz ve Kuşat, 2020), Beymelek Lagünü (Antalya) (Özbolat, 2022)], Atikhisar Baraj Gölü (Çanakkale) (Demirkıran ve Özekinci, 2022) ve Van İlinde bulunan baraj gölleri (Demir, 2023) için uzatma ağlarında CPUE hesaplanmıştır. Uzatma ağları için elde edilen bulguları, önceki çalışmaların birçoğuyla hedef tür veya CPUE birim farklılığı nedeniyle karşılaştırmak mümkün olmamıştır. Bu çalışmada monofilament uzatma ağında (50, 60, 65, 70, 75, 80 ve 90 mm ağ göz genişliklerinde) av sezonu için elde edilen CPUE değeri (0,030±0,015 kg/m/gün), Balık (2011) tarafından Beyşehir Gölü'nde 28, 40, 50 ve 60 mm ağ göz genişliğindeki monofilament (22,39 g/m) ve multifilament uzatma ağlarında (11,12 g/m) hesaplanan değerlerden daha yüksektir. Ancak daha küçük ağ göz genişlikleri (18, 20, 22, 26, 30 ve 36 mm) kullanan diğer bir çalışmadan (Balık ve Çubuk 2001)'den ise oldukça düşüktür. Değerlerdeki farklılıkların, habitat ve hedef tür farkı ile Balık (2001) ve Balık ve Çubuk (2001)'den daha küçük ağ gözleri kullanılmasından kaynaklandığı düşünülmektedir. Balıkların uzatma ağına yakalanmasında ağ gözü açıklığı önemli rol oynamaktadır (Stewart 1987). Av araçlarının birim av miktarları, yakalanması hedeflenen balık türünün yoğunluğuna bağlıdır (Stewart 1987).

Hedef türün ve göz açıklıklarının kısmen benzediği diğer bir çalışmada ise Demir (2023), Van baraj göllerinde sazan için CPUE 55, 60, 65 ve 70 mm ağ göz genişliklerinde uzatma ağında Sarımemet Baraj Gölünde 0,85 kg/100 m/posta, Koçköprü Baraj Gölünde 0,99 kg/100 m/posta, Zernek Baraj Gölünde 0,67 kg/100 m/posta olarak saptanmıştır.ve bu çalışmadan daha yüksektir. Farklılığın habitat farklılığından kaynaklandığı düşünülmektedir. Habitatın yanı sıra birim av miktarını (CPUE) etkileyen su sıcaklığı, besin durumu, oksijen miktarı, akıntı, ay ışığı, gece ve gündüz sürelerindeki değişim gibi pek çok faktör vardır. Bilindiği üzere, pasif olan uzatma ağları ile avcılıkta balıkların aktiviteleri çok önemlidir. Balıkların aktiviteleri de bu faktörlere bağlı olarak değişiklik gösterebilmektedir (Balık ve Çubuk, 2001).

Habitatın aynı olduğu, hedef türün ve göz açıklıklarının kısmen benzediği diğer bir çalışmada ise (Şen, 2016), Demirköprü Baraj Gölü'nde (Manisa) sazan için 65, 70, 75, 80 mm ağ göz genişliğine sahip multifilament uzatma ağlarında ve toplamda CPUE sırasıyla 21,90±10,03; 15,98±7,59; 9,44±5,28; 14,11±6,48 ve 15,36±7,34 g/m/operasyon olarak tespit edilmiş olup, bizim değerlerimiz daha düşüktür. Farklılığın bu çalışmada monofilament ağ kullanılmasından ve sazana ilaveten Yayın ve *Carassius* sp. balıklarının da hedeflenmesinden kaynaklandığı düşünülmektedir. Monofilament (misina) ağlar şeffaf olmalarından dolayı multifilament ağlara oranla balıklar tarafından daha zor görülürler. Bu sebeple monofilament ağların av verimliliği daha yüksektir (Karlsen ve Bjarnason, 1987; Korkmaz ve Kuşat, 2020).Aynı göz genişliğine sahip multifilament uzatma ağlarının monofilament ağlardan daha düşük CPUE'ye sahip olduğu diğer çalışmalarda da vurgulanmıştır (Balık, 2001; Balık ve Çubuk, 2001; Korkmaz ve Kuşat, 2020).

Ülkemiz içsularında pinterlerle kerevit (*Pontastacus leptodactylus* Eschscholtz, 1823) avcılığında CPUE değerleri, Atikhisar Baraj Gölü'nde (Çanakkale) adet/tuzak/gün (Demirkıran ve Özekinci, 2022), Fırat Nehri üzerinde bulunan Keban Baraj Gölü'nde (Elazığ) (Dartay, 2023; Demirol ve Yüksel, 2014) ve Hirfanlı Baraj Gölü'nde (Kırşehir) (Cilbiz ve diğ., 2021) g/pinter/gün olarak hesaplanmıştır. Bu çalışmada ise CPUE sazan ve yayın için pinterde kg/adet/gün olarak hesaplanmış olup, çalışma bulguları hedef tür farklılığı nedeniyle önceki çalışmalarla karşılaştırılamamıştır.

Paragat için Ülkemiz içsularında CPUE değerlerini belirlemeye yönelik çalışmaya rastlanılmamış olup, sınırlı sayıda çalışmanın (Şensurat ve Akyol, 2019; Dereli ve diğ., 2015) denizlerdeki küçük ölçekli balıkçılıkta yürütüldüğü belirlenmiştir. Yayın türünü hedefleyen paragatta CPUE değerini kg/100iğne/gün olarak hesaplayan bu çalışmanın Ülkemiz içsularında

bu konuda yürütülmüş ilk çalışma olması nedeniyle literatürdeki önemli bir boşluğu dolduracağı düşünülmektedir.

Sonuç olarak, bu çalışma ile Demirköprü Baraj Gölü'nde balıkçılık çabası ve av araçlarının CPUE'leri belirlenmiş olup, sazan ve yayın türlerini hedefleyen pinter için ve yayın türünü hedefleyen paragat için CPUE değerleri ilk kez ortaya konmuştur. Bu çalışmaların gelecekte de devam ettirilmesi, CPUE vasıtasıyla balık stoklarına ilişkin dolaylı bilgi edinmek ve bu stoklar üzerinde sağlıklı balıkçılık yönetimi kararları alabilmek için gereklidir.

TEŞEKKÜR

Bu çalışma, TÜBİTAK tarafından desteklenen 2209-A Üniversite Öğrencileri Araştırma Projeleri Destek Programı (1919B012322934 başvuru numaralı) kapsamında yürütülmüş olup, projeye sağladığı desteklerden dolayı Türkiye Bilimsel ve Teknolojik Araştırma Kurumu'na (TÜBİTAK) teşekkür ederiz. Saha çalışmalarında avcılık verilerini paylaşarak projeye önemli katkılarda bulunan S.S. Köprübaşı Balıkçılık Kooperatifi Başkanı Sayın Ramazan UYSAL'a ve değerli kooperatif üyelerine teşekkürlerimizi sunarız.

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BROYLER PİLİÇLERDE BACAK SAĞLIĞI VE YÜRÜME FONKSİYONUNUN DEĞERLENDİRİLMESİ

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ÖZET

Artan gıda talebi, broyler sektöründe hızlı büyüme ve yüksek canlı ağırlık hedeflerinin öncelikli hale gelmesine yol açmıştır. Bu durum iskelet gelişimi ile büyüme hızı arasındaki dengesizliğe, bacak kemikleri, eklemler ve bağ dokuların zayıflamasına yol açmakta ve broyler piliçlerde topallık ile iskelet kas sistemi problemlerini arttırmaktadır. Bacak sağlığının korunması, üretim performansı ile hayvan sağlığı ve refahı açısından kritik öneme sahiptir. Topal piliçlerin hareket edememesi ve yem ile suya ulaşmakta zorlanması, hem ağrı ve ızdıraba neden olur hem de üretim kayıpları ile gıda güvenliği risklerini artırmaktadır. Broyler piliçlerin yürüme fonksiyonunu ve sürü refahını değerlendirmek için geliştirilen yöntemler, gözlemsel ve teknolojik yaklaşımlar olarak sınıflandırılabilir. Gözleme dayalı yöntemler, **hayvanın davranış ve fiziksel durumunu incelemeye dayalı olup**, yürüyüş skorlama, ayak tabanı ve diz eklemi yangısı skorlamaları ile Yatmanın Gecikmesi Testi gibi uygulamaları içerir. Teknolojik yöntemler ise ivme ölçerlerin kullanıldığı sensör tabanlı otomatik ölçümler, bilgisayar görüntüleme tekniklerinin kullanıldığı optik akış ve kinetik analizler ile kızılötesi termografi değerlendirmeleri gibi uygulamaları kapsar**.** Bu yöntemler, **ekipman gereksinimi, uygulama kolaylığı ve gözlemci eğitim gereksinimi** gibi özellikler bakımından farklılık göstermektedir. Piliçlerde bacak sağlığı ve yürüme fonksiyonunun değerlendirilmesinde kullanılacak yöntemin seçimi, ölçümün amacı, uygulanabilirlik ve doğruluk kriterleri dikkate alınarak yapılmalıdır. Bu bildiride, broyler piliçlerde bacak fonksiyonlarını değerlendirmek için geliştirilen gözleme dayalı manuel yöntemler ile teknolojik yöntemleri içeren güncel bilimsel gelişmeler özetlenmiştir. Ayrıca, hassas hayvancılık uygulamalarına dayalı yeni yöntemlerin ticari koşullara uyarlanması ve doğrulanmasının, broyler piliçlerin refahını izleme ve üretim performansını arttırmadaki potansiyel katkıları tartışılmıştır.

Anahtar Kelimeler: Broyler Piliç, Değerlendirme Yöntemleri, Bacak Sağlığı, Yürüme Fonksiyonu

ASSESSMENT OF LEG HEALTH AND LOCOMOTOR FUNCTION IN BROILER CHICKENS

ABSTRACT

Rapid growth and high body weight targets have been prioritised in the broiler industry due to rising global demand for food. This has led to an imbalance between the development of the skeleton and its growth rate, resulting in weaker leg bones, joints, and connective tissues, and an increase in the prevalence of lameness and skeletal disorders in broiler chickens. Maintaining leg health is crucial for production efficiency and animal welfare. Lame birds have difficulty moving and accessing feed and water, which causes them pain and distress and contributes to production losses and increased food safety risks. Methods developed to assess walking ability and flock welfare in broiler chickens can be broadly classified as either observational or technological. Observational methods involve directly examining behaviour and physical condition, including gait scoring, footpad and hock burn scoring, and the latency-to-lie test. Technological approaches include sensor-based automated measurements using accelerometers and optical flow, as well as kinematic analyses employing computer vision techniques and infrared thermography assessments. These methods differ in terms of their equipment requirements, how easily they can be implemented, and whether observer training is necessary. The choice of an appropriate method for evaluating leg health and walking ability in broiler chickens should consider the purpose of the measurement, as well as the feasibility and accuracy criteria. This paper summarises recent scientific advancements and examines both manual observation-based methods and technological approaches developed for assessing leg function in broilers. Furthermore, this paper discusses the potential contributions of precision livestock technologies to monitoring broiler welfare and enhancing production performance, including their adaptation and validation under commercial conditions

Keywords: Broiler Chicken, Assessment Methods, Leg Health, Locomotor Function

GİRİŞ

Hızlı büyüme yönünde selekte edilen ağır yapılı broyler piliçlerde, gelişimsel, dejeneratif ve enfeksiyöz kökenli bacak problemleri ve buna bağlı topallık sık görülmektedir. Bu durum endüstride verim düşüklüğü ve ekonomik kayıplara yol açmaktadır (Bradshaw vd. 2002; Caplen vd. 2012). Topallık, yürüyüş yeteneğinde belirgin bozulma olarak tanımlanır ve sahada manuel olarak değerlendirilmesi zaman alıcı, maliyetli ve hayvanları rahatsız edici olduğundan genellikle üretim döngüsünün sonunda ve çoğunlukla bir kez olmak üzere sürüden alınan bir örneklem üzerinde gerçekleştirilmektedir (Weeks vd. 2000; Mullan vd. 2009). Broylerlerde yaygın olarak kullanılan geleneksel deri lezyonları ve yürüyüş skorlama yöntemleri eğitimli değerlendiricilerin gözlemleyerek ve manuel olarak gerçekleştirdikleri değerlendirmeler olması nedeniyle subjektif, zaman alıcı ve operasyonel açıdan maliyetlidir (Kestin vd. 1994; Reiter ve Bessei 1997; Butterworth 1999; Bessei, 2006; Pearce vd. 2023; Kwon vd. 2024). Broyler piliç yetiştirme sistemlerinde ve özellikle barındırma yoğunluğunun yüksek olduğu koşullarda bacak hastalıkları ve yürüyüş bozukluğu sağlık ve performansı olumsuz etkiler ve sürü ve birey düzeyinde yapılacak geleneksel değerlendirmelerle başarı şansı daha düşük olmaktadır (Bokkers ve de Boer 2009; Dawkins 2017; Pereira vd. 2025). Geleneksel metotlarla yapılan bireysel izleme yöntemleri, binlerce broyleri barındıran ticari işletmelerde pratik **zorluklara neden olmaktadır ve sürü hareketinin izlenmesine ilişkin hayvan refahı değerlendirmelerinin de yapılmasında güçlükler meydana gelmektedir (**Gebhardt-Henrich vd. 2021; Pereira vd. 2025;). Ayrıca bu değerlendirmeler sınırlı sayıda piliç üzerinde yapılmaktadır ve elde edilen sonuçlar hem incelenen bireyin yaşamının tamamındaki refah durumunu yansıtmak bakımından hem de tüm sürüye ilişkin olası sağlık ve refah problemlerinin zamanında belirlenmesinde yeterli olmamaktadır. Bu nedenle, canlı piliçlerden sürekli veri toplayabilen sistemlerle refah parametrelerinin düzenli ve otomatik olarak izlenmesi piliçlerin refahı standartlarının karşılanması yanı sıra yetiştiriciler ve hayvan ıslahçılarının ihtiyaç duydukları veri setlerini elde edebilmeleri için çok önemlidir (Dawkins vd. 2009; Wurtz ve Riber, 2024). Son dönemde davranış ve sağlık göstergeleri dahil olmak üzere hayvan refahının gerçek zamanlı ve otomatik izlenmesini sağlayabilecek Hassas Hayvancılık Teknolojilerinin (PLF) geliştirilmesine yönelik çabalar artmaktadır (Dawkins vd. 2017; Pearce vd. 2023). Bu amaçla bilgisayar teknolojisi ve yapay zekâ tabanlı algoritmalara dayalı çeşitli otomatik izleme sistemleri geliştirilmiştir (Dawkins vd. 2013; Pereira vd. 2025). Bu sistemler arasında ivmeölçerlerin kullanıldığı sensör tabanlı otomatik ölçümler, bilgisayar görüntüleme tekniklerinin kullanıldığı optik akış analizleri ve kinetik analizler ile kızılötesi termografi **gibi yöntemler** öne çıkmaktadır (Kashiha vd. 2013; Weimer vd. 2019; Pearce vd. 2023). Bu teknolojiler kullanılarak broylerlerde topallık, davranış, beden sıcaklığı, aktivite ve bazı sağlık göstergelerinin izlenmesine yönelik çalışmalar yapılmaktadır. Bu alandaki ilerlemeler, kanatlı refahının izlenmesine yönelik daha güvenilir ve işletme koşullarına uyarlanabilir teknolojilere duyulan ihtiyacı **açık bir biçimde ortaya koymaktadır** (Aydin 2017; Okinda vd. 2020; Dawkins vd. 2012). Bu bildiride, broyler piliçlerde **ayak ve bacak sağlığı ile topallığın** değerlendirilmesinde kullanılan gözleme dayalı manuel yöntemler ile yenilikçi teknolojik yöntemler ele alınmış, konuya ilişkin güncel bilimsel gelişmeler özetlenmiş ve hassas hayvancılık uygulamalarına dayalı yeni yöntemlerin ticari koşullara uyarlanması ve doğrulanmasının, broyler piliçlerin refahını izleme ve üretim performansını **arttırmadaki potansiyel katkıları tartışılmıştır.**

2. METOT

Broyler piliçlerde bacak sağlığı ve yürüme fonksiyonunun değerlendirilmesini ele alan güncel hakemli bilimsel makaleler açık erişimli kaynakları kapsayacak şekilde taranmıştır. Bu kapsamda PubMed, Web of Science ve Google Scholar veri tabanlarından yararlanılmıştır.

Anahtar kelimeler arasında “broiler welfare”, “lameness”, “behavioral indicators”, “locomotor function”, “leg health” ve “assessment methods” yer almıştır. Sistematik tarama sonucunda incelenen çalışmalar, bacak sağlığı, topallık ve yürüme fonksiyonunun değerlendirilmesine ilişkin somut bulgular sunan, gözleme dayalı ve teknoloji tabanlı yöntemleri ayrı ayrı yada karşılaştırmalı biçimde ele alan araştırmalarla sınırlandırılmıştır. İncelenen bilimsel çalışmalardan elde edilen bulgular doğrultusunda, broyler piliçlerde bacak sağlığı ve yürüme fonksiyonunun değerlendirilmesinde kullanılan **gözleme dayalı yöntemler ile teknoloji tabanlı ölçüm yaklaşımları karşılaştırmalı olarak tartışılmıştır.**

3. BROYLERLERDE AYAK VE BACAK SAĞLIĞI İLE YÜRÜYÜŞÜN GÖZLEME DAYALI DEĞERLENDİRİLMESİ

Ayak tabanı ve diz eklemi yangısı, broyler piliçlerde ayak tabanı ve diz bölgesindeki derinin sert altlıkla uzun süre temas etmesi sonucu ortaya çıkan bir temas dermatitidir ve deri hasarına, iltihaplanmaya ve rahatsızlığa yol açar (Berg 2004; Kjaer vd. 2006; Meluzzi vd. 2008; Kwon vd. 2024). Bu **deri yangıları**, broyler üretiminde yaygın karşılaşılan ve ayak tabanı ile dizlerde ağrıya, iltihaba ve ülserasyona yol açan **temas dermatit türü lezyonlardır**. Özellikle piliçler nemli ve kirli altlık üzerinde uzun süre kaldığında bu lezyonlar daha da artar ve ciddi refah ve ekonomik sorunlara neden olur (Broom ve Reefmann 2005; Dawkins vd. 2009). Bu lezyonların yaygınlığı ve düzeyi hayvan refahının önemli göstergeleri olarak kullanılmakta ve bu değerlendirmeler genellikle **sürüyü temsil eden bir örneklem üzerinde** ve manuel olarak, **yoğun iş gücüyle** gerçekleştirilmektedir (Greene vd. 1985; Berg 2004; Haslam vd. 2007; de Jong vd. 2012; Dawkins vd. 2017; Liu vd. 2023; Kwon vd. 2024). Ayak tabanı yangılarının belirlenmesi ve şiddetinin değerlendirilmesi amacıyla Welfare Quality Kanatlı Refahı Değerlendirme Protokolünde yer alan standartlaştırılmış bir skorlama sistemi yaygın şekilde kullanılmaktadır (Welfare Quality 2009). Bu sistemde incelenen piliçlerin ayak tabanındaki lezyon durumu beş dereceli bir skala ile mukayase edilerek incelenmektedir (0: normal; 4: şiddetli ülserasyon ve inflamasyon) (Berg 2004; Heitmann vd. 2018). Bu değerlendirmede hayvanların ayak tabanındaki lezyonların yaygınlığı, şiddeti ve inflamasyonun düzeyi dikkate alınarak skorlama yapılmaktadır (Berg 2004; Heitmann vd. 2018; Liu vd. 2023; Kwon vd. 2024**).** Broyler piliçlerde refahın değerlendirilmesinde sıkça kullanılan diğer bir yöntem diz eklemi derisindeki yangı ve lezyonların incelenmesidir. Diz eklemi yangısının belirlenmesi ve lezyonların şiddetinin değerlendirilmesi için de yaygın olan yöntem Welfare Quality Kanatlı Refahı Değerlendirme Protokolü’nde standartlaştırılmış skorlama sistemin kullanılmasıdır. Diz eklemi yangısında da diz eklemi bölgesinde deri lezyonlarının durumu beş dereceli bir skala ile değerlendirilir (0: normal; 4: en şiddetli ülserasyon ve inflamasyon) (Welfare Quality 2009; Pereira vd. 2025). Ayak tabanı ve diz eklemi yangılarının şiddeti arttıkça, lezyon çevresindeki enfekte ve nekroze alanlar kızılötesi termografi (IRT) kullanılarak invaziv olmayan bir şekilde tespit edilebilir ve bu yöntem deri sağlığının değerlendirilmesinde kullanılabilmektedir (Wilcox vd. 2009; Weimer vd. 2019; Liu vd. 2023). Broylerlerde kas ve iskelet sistemi problemlerinin tespit edilmesi için kullanılan gözleme dayalı diğer bir değerlendirme yöntemi yürüyüş skorlamasıdır (Kestin vd. 1994; Reiter ve Bessei 1997; Butterworth, 1999). Yürüyüş skorlama sistemleri, hayvanlarda yürüyüş kalitesini ve topallık durumunu belirlemek amacıyla kullanılan değerlendirme yöntemleridir. Manuel yürüyüş skorlama yöntemi, genellikle en yaygın kullanılan yöntemdir (Silvera vd. 2017; Wurtz ve Riber 2024). Bristol Yürüyüş Skorlama Sistemi ve Welfare Quality® Protokolü, broyler piliçlerin bir gözlemci tarafından izlenerek yürüyüşlerinin 6 puanlı (0 puan: normal yürüyüş; 5 puan: yürüyemeyen hayvanlar) bir skala ile değerlendirilmesini sağlar ve bu yöntem altın standart olarak kabul edilir (Kestin vd. 1992; Hartcher ve Lum 2020; Wurtz ve Riber 2024). Saha koşullarında, kümesteki popülasyonu temsil edecek şekilde rastgele seçilen 100–150 hayvanlık

bir örneklemdeki tüm piliçler, tek bir gözlemci tarafından bireysel olarak izlenir ve yürüyüşün normal olup olmadığı ve var ise topallık durumunun derecesine göre skorlama yapılır (Kestin vd. 1992; Welfare Quality 2009; Liu vd. 2023). Altı puanlı yürüyüş skorlama yöntemi hızlı, ekipmansız ve geçerli bir değerlendirme sağlar, ancak değerlendiricilerin eğitimini ve uygulamanın düzenli kontrol edilmesi gerektirir. Ayrıca sürü veya işletmeler arasında gözlemciler arası güvenilirlik derecesi düşük olabilir ve hayvanların yürümeye zorlanması skorlama sırasında yanıltıcı sonuçlara neden olabilir (Mench 2004; Dawkins vd. 2004; Webster vd. 2008; Welfare Quality, 2009; Wurtz ve Riber 2024). Bristol Yürüyüş Skorlama Sistemi revize edilerek piliçlerin yürüyüşünün yukarıdan ve hayvan seviyesinden olmak üzere iki değerlendirici tarafından izlenmesi yönteme dahil edilmiştir (Garner vd. 2002). Broyler piliçlerde bacak sağlığının değerlendirilmesinde kullanılan invaziv olmayan yöntemler arasında hayvan davranışlarının gözlenmesine dayanan Yatmanın Gecikmesi Testi (Latency to Lie) bulunmaktadır (Weeks vd. 2002). Bu test, kanatlı hayvanların ne kadar süre ayakta kalabildiğini ölçerek yürüme yeteneğini değerlendiren, doğrulanmış ve nesnel bir davranışsal testtir. Testin suyun varlığı veya yokluğu, bireysel ya da grup halinde uygulanması ve bir kap içinde ya da kümes içinde sınırlama olmadan yapılması gibi çeşitli varyasyonları bulunmaktadır (Weimer vd. 2020; Wurtz ve Riber, 2024). Su kullanılarak yapılan test yönteminde, hayvanlar sığ suyla kaplanmış bir alana veya kap içerisine yerleştirmekte ve oturana kadar geçen süre kronometre ile ölçülmektedir (Weeks vd. 2002; Wurtz ve Riber 2024). Bacaklarında bir problem olmayan ve sağlıklı bacaklara sahip olan hayvanlar daha uzun süre ayakta kalabilirken, ağrısı veya topallığı olanlar kısa sürede yatmaktadır (Berg ve Sanotra 2003;Silvera vd. 2017). Yakalama stresini azaltmak amacıyla geliştirilen ve su kullanılmadan yapılan Yatmanın Gecikmesi Testi ise kümes ortamında yapılmakta ve yatan broyler piliçler arasından örneklemle belirlenenlere yaklaşılarak hafif bir uyarı ile ayağa kalkmaları teşvik edilmektedir. Hayvanın tekrar yere yatmasına kadar geçen süre kronometre ile ölçülerek onun ne kadar süre ayakta kaldığı belirlenmektedir. Bacakları sağlıklı ve güçlü olan piliçler daha uzun süre ayakta kalabilirken, ağrılı veya zayıf bacaklara sahip piliçler daha kısa sürede yatmaktadır (Bailie ve O'Connell 2014; Okinda vd. 2020).

4. BROYLERLERDE BACAK SAĞLIĞI VE YÜRÜYÜŞÜN TEKNOLOJİK DEĞERLENDİRİLMESİ

Sağlıklı bir broylerin belirli bir süre boyunca düzenli adımlarla kesintisiz şekilde yürümesi, iyi refahın temel göstergelerinden birisidir ve bu davranış **makineler tarafından görece kolay algılanabilmektedir** (Caspersen vd. 1985; Kleanthous vd. 2022; Dawkins 2024). Broylerlerde hızlı büyüme, artan vücut ağırlığı ve morfolojik değişiklikler, aktivitenin azalmasına ve bunun sonucunda yürüyüş bozukluklarının ortaya çıkmasına yol açabilmektedir (Bokkers ve Koene 2003; Pearce vd. 2023). Bu çerçevede ivmeölçer sensörler, adım frekansı, duruş değişiklikleri ve aktivite düzeyi gibi hareket parametrelerini kaydederek broylerlerde yürüme ve davranış örüntülerini izler ve topallığın erken ve objektif tespitini sağlar (Abeyesinghe vd. 2021; Pearce vd. 2023; Wurtz ve Riber 2024). Lokomotor dinamikleri kaydetmek için kullanılan vücuda takılan ivmeölçerler, hayvan aktivitesini izlemek amacıyla giderek daha fazla kullanılmakta olup, hayvan refahı ve hastalık izlemede zaman kazandıran, sürekli ve nesnel bir yöntem sunmaktadır (Brown vd. 2013; Abeyesinghe vd. 2021; Pearce vd. 2023; Wurtz ve Riber, 2024). Sensörlerin uygulanmasında iki temel yöntem bulunmaktadır. İlk yöntem, cihazın bir sırt çantası aracılığıyla hayvanın sırtına yerleştirilmesidir (Stadig vd. 2018; Dawson vd. 2021). İkinci yöntem ise sensörün doğrudan deriye, Hypafix® gibi bantlarla yapıştırılmasıdır (Nathan vd. 2012; Hall vd. 2016; Pearce vd. 2023). Manuel yapılan geleneksel yürüyüş skorlama yöntemi, öznel ve zaman alıcı olup genellikle az sayıda hayvanı kapsadığı için broylerlerin yaşam boyu refahını izlemede sınırlıdır (Mullan vd. 2009; Caplen vd. 2012). İvmeölçerler ise

bireysel düzeyde sürekli ve objektif veri sağlayarak topallığı erken ve hassas biçimde saptamayı mümkün kılabilir ve sensör ve video tabanlı otomatik sistemlerle birlikte kullanıldığında manuel değerlendirmenin kısıtlılıkları azaltır (Pearce vd. 2023; Wurtz ve Riber 2024). Kinetik analizler, piliçlerin yürüyüş sırasında ayaklarının yere uyguladığı kuvvet ve basıncı ölçerek yürüyüş yeteneği ve bacak sağlığını sayısal olarak değerlendirmeyi amaçlar. Bu analizlerde temel olarak ayak kuvvetleri ve basınç dağılımı, adım ve yürüyüş özellikleri incelenir (Nääs vd. 2010; Sandilands vd. 2011; Wurtz ve Riber 2024). Ölçümler, yürüyüş yoluna gömülü kuvvet plakaları veya piezoelektrik sensörler aracılığıyla gerçekleştirilir. Piliçler yürüyüş yoluna yerleştirilir ve doğal veya yönlendirilmiş yürüyüşleri sırasında sensörler ilgili verileri kaydeder (Nääs vd. 2010; Sandilands vd. 2011; Fodor vd. 2025). Kinetik analizler, bacak veya ayaktaki ağrı ile iskelet ve kas dokularındaki sorunlar nedeniyle beden ağırlığın bacaklar üzerinde taşınmasına ilişkin değişiklikleri tespit ederek topallığı belirler (Nääs vd. 2010; Okinda vd. 2020; Wurtz ve Riber 2024). Topallık genellikle ayak kuvvetlerinde asimetri, maksimum dikey kuvvet değişiklikleri, yürüyüş hız ve adım özelliklerindeki değişiklikler ve ayak tabanı basınç dağılımındaki farklılıklarla ortaya konmaktadır (Corr vd. 2003; Nääs vd. 2010; Sandilands vd. 2011; Silvera vd. 2017). Bilgisayarlı görüntüleme yöntemleri kapsamında kullanılan o**ptik akış**, broylerlerin yürüme yeteneği, topallık ve duruş değişimlerini video üzerinden otomatik olarak izleyen bir yöntemdir. Optik akış **b**ireylerin sürekli takip edilmesine olanak sağlar ve en az veri ile yürüyüş skorları hakkında bilgi verir. Optik akış desenlerinin çarpıklık ve basıklığı zayıf yürüyüş yeteneğiyle ilişkilidir **(**Dawkins vd. 2012; Dawkins vd. 2013; Okinda vd. 2020; Wurtz ve Riber 2024). Grup düzeyinde elde edilen desenler, anormal yürüyen broyler oranı ve genel bacak sağlığı sorunlarıyla korelasyon göstermektedir (Dawkins vd. 2012; Pearce vd. 2023; Pereira vd. 2025). Böylece optik akış, hem birey hem de grup düzeyindeki refah sonuçlarını dolaylı biçimde yansıtan, ucuz ekipmanla sürekli ve otomatik veri üretebilen müdahalesiz bir ölçüm yöntemi olarak öne çıkmaktadır. (Dawkins vd. 2009; Dawkins vd. 2017; Pearce vd. 2023**)**. Özellikle sürü yaşamının ilk iki haftasında elde edilen optik akış desenleri, ilerleyen haftalardaki mortalite ve diz eklemi yangısı prevalansı gibi temel refah göstergeleriyle anlamlı şekilde ilişkili bulunmuştur (Pereira vd. 2025). Bu da yöntemin erken uyarı amacıyla kullanılabileceğini ve farklı çevre ile yönetim koşullarında bile ticari kullanım potansiyeline sahip olduğunu göstermektedir (Dawkins vd. 2021; Wurtz ve Riber ve 2024; Pereira vd. 2025).

5. SONUÇ VE ÖNERİLER

Bu çalışmada incelenmiş bilimsel araştırmalarda sunulan bilimsel gelişmelerden yola çıkarak ulaşılan sonuçlar ve öneriler özetle aşağıda sunulmuştur:

- Broyler piliçlere bacak sağlığı ve refahı artırmak için uygun besleme, barınma koşulları ve refahı destekleyen yönetim uygulamaları sağlanmalıdır. Ayrıca, piliçlerde bacak problemlerinin oluşumu önlenmeli ve topallık ile diğer sağlık sorunlarının gelişmemesi için düzenli izleme yapılmalıdır.

- Broylerlerde refahın izlenmesi, geleneksel yöntemlerin yanı sıra kamera ve bilgisayar tabanlı tekniklerle desteklenmelidir. Özellikle sürü ve bireysel düzeyde davranış, hareketlilik ve sağlık takibi için mevcut sürü yönetim sistemlerine, optik akış gibi bilgisayarlı görüntüleme yöntemleri entegre edilmelidir.

- Gelecek dönemde yapılacak çalışmalar, hassas hayvancılık uygulamalarının broyler genotiplerine özgü davranış analizleri ile farklı barındırma sistemleri dikkate alınarak, doğruluk ve güvenilirliği artıracak şekilde ticari koşullara uyumlu hâle getirilmelidir. Elde edilen veriler, modern kanatlı üretiminde hayvan refahı, sürdürülebilirlik, genomik ıslah ve yönetim stratejilerinin geliştirilmesinde etkin bir şekilde kullanılabilir.

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YAKALAMA YÖNTEMİNİN BROYLER PİLİÇLERİN REFAHI VE KARKAS KALİTESİ ÜZERİNE ETKİSİ

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ÖZET

Broyler eti üretimi, dünya genelinde en hızlı büyüyen hayvansal protein sektörüdür. Bu nedenle diğer çiftlik hayvanlarına göre çok daha fazla sayıda broyler yakalanmakta, taşınmakta ve kesilmektedir. Taşınmak üzere hayvanların yakalanıp nakil ünitelerine yerleştirilmesi, **hayvana temas edilmesi ve alışılmadık çevresel koşullar** piliçlerde **akut strese neden olmaktadır.** Piliç yakalama işlemi, kesim öncesi üretim zincirinin en hassas aşamalarından biridir ve hayvan refahı ve karkas kalitesi açısından büyük öneme sahiptir. Manuel yakalamada, genellikle çalışanlar piliçleri bacaklarından tutularak, başları aşağıda olacak şekilde taşıma kasa veya modüllerine yerleştirir. Mekanik yakalamada ise piliçler el değmeden kümes zemininden toplanıp taşıma kasa veya modüllerine aktarılırlar. Her iki yakalama yönteminin meydana gelen hayvan stresi ve karkas kayıpları bakımından etkileri farklılık göstermektedir. Piliçlerin uygun şekilde yakalanmaması sonucu ortaya çıkan kanat ve bacak kırıkları, morluklar ve deri sıyrıkları gibi lezyonlar karkas reddine ve ekonomik kayıplara neden olmaktadır. Ayrıca, piliçlerin yakalanması ve yüklenmesi görevli personel açısından önemli ölçüde ergonomik zorluklar ve iş güvenliği riskleri içermektedir. Bu nedenle, piliç yakalamada kullanılacak yöntemin, **hayvan refahı, çalışan sağlığı ve ekonomik etkiler arasında hassas bir dengeyi sağlaması gerekir.** Broyler endüstrisi, genetik seleksiyonlar, hayvan refahı gereklilikleri, tüketici baskısı ve hassas teknoloji alanındaki yeniliklerin etkisiyle önemli bir yapısal dönüşüm sürecine girmiştir. Bu bildiride **broyler piliçleri yakalamak için kullanılan yöntemlerin hayvan refahı, karkas kalitesi, ergonomik ve ekonomik sonuçlar üzerindeki etkilerine ilişkin en** güncel bilimsel gelişmeler özetlenmiş, yakalama yöntemleri hayvan refahı, çalışan sağlığı ve çiftçi geliri arasında hassas bir denge sağlama potansiyeli bakımından tartışılmıştır.

Anahtar Kelimeler: Broyler Piliç, Hayvan Refahı, Karkas Kalitesi, Yakalama Yöntemi

THE EFFECTS OF CATCHING METHODS ON BROILER WELFARE AND CARCASS QUALITY

ABSTRACT

Broiler production is currently the fastest growing sector of the animal protein industry worldwide. Consequently, a much larger number of broilers are captured, transported and slaughtered than other farm animals. The process of handling birds for transport, including capturing them and placing them in crates for transportation, as well as their exposure to unusual environmental conditions, can induce acute stress. The process of catching the animal is one of the most critical stages in the chain of events that take place before slaughter, and it is of great importance for both the animal welfare and the quality of the carcass. In manual catching, birds are grasped by the legs and load them into trasport crates or modules while the birds are held upside down. In contrast, in mechanical catching, birds are collected from the floor without direct human contact and transferred into conveyor systems and into crates. These two methods differ in terms of the animal stress they induce and the resulting carcass losses. Improper catching practices can lead to lesions such as wing and leg fractures, bruising and skin abrasions, which increase carcass condemnation rates and cause economic losses. In addition, broiler catching and loading tasks present considerable **ergonomic challenges** and occupational safety risks for personnel. The choice of catching method must carefully balance animal welfare, worker safety and financial outcomes. The broiler industry has undergone significant structural changes in recent years due to genetic selection, animal welfare requirements, consumer demands and the adoption of precision technologies. This paper summarises the latest scientific research on the impact of broiler catching methods on animal welfare, carcass quality, ergonomics and economic performance. It also discusses how different catching techniques could help to strike a balance between animal welfare, worker health and safety, and farm profitability.

Keywords: Broiler Chicken, Animal Welfare, Carcass Quality, Catching Method

1. GİRİŞ

Küresel gıda talebinin artması, kanatlı sektörünün büyümesini hızlandırmıştır ve çiftlikten kesimhanelere taşınan tavuk sayısını oldukça çok arttırmıştır (Delezie vd. 2005; Dutra vd. 2021;Delanglez vd. 2025). Kümes veya kafes içinde yetiştirilen tavukların yakalanması ve ele alınması, nakil kasa veya modüllerine yerleştirilmesine kadar geçen yakalama ve taşıma süreci stres, yaralanma ve ölüm riskine yol açabilmektedir (Kittelsen vd. 2018; Wolf vd. 2019; Delanglez vd. 2025). Bu süreçteki işlemlerin operasyonel verimliliğinin hayvan refahı ve ekonomik çıktılar üzerindeki etkisi çok önemlidir (Cockram vd. 2020; Weeks vd. 2024).

Piliç yakalama manuel veya mekanik olarak gerçekleştirilebilirken birçok ülkede yakalama işlemi hâlâ büyük ölçüde manuel yöntemlere ve özellikle baş aşağı yakalama yöntemine dayanmaktadır (Delezie vd. 2006; Langkabel ve Baumann, 2015; Beňo vd. 2021). Ancak baş aşağı yakalama yöntemi hayvan refahı açısından önemli sorunlar meydana getirmektedir (Delezie vd. 2006; Beňo vd. 2021; Nielsen vd. 2022). Ayrıca farklı yakalama yöntemlerinin hem çiftlik ekonomisi hem de hayvan refahı üzerine değişen ölçülerde etki yapabileceği bildirilmektedir (Jacobs vd. 2017; Kittelsen vd. 2018; Cockram vd. 2020; Delanglez vd. 2024b).

Yakalama süreci çalışanlar açısından kümes içi zorlu çevre koşulları, fiziksel zorlanma ve yorgunluk, yaralanma riski ve artan iş yükü nedeniyle önemli bir iş sağlığı ve güvenliği sorunu oluşturmaktadır (Nijdam et al., 2004; Delezie ve ark., 2006; Dutra vd. 2021; de Lima vd. 2019). Son yıllarda geliştirilen mekanik yakalama sistemleri, iş gücünü azaltma ve hayvanlarda oluşan stresi sınırlama potansiyeli nedeniyle sektörde giderek daha fazla önem kazanmaktadır. (Duncan vd. 1986; Dutra vd.2021; Delanglez vd. 2025). Hangi yakalama yönteminin tercih edileceği, çoğunlukla hayvan refahı, çalışan ergonomisi ve çiftlik ekonomisi arasındaki dengenin kurulmasına bağlıdır. Bununla birlikte, broylerlerde baş aşağı, dik ve mekanik yakalama yöntemlerini karşılaştıran çalışmalar sınırlı olup, bu kapsamda hayvan refahı daha fazla incelenmiş ancak ergonomik ve ekonomik etkilere ilişkin çalışmalar oldukça azdır (Lacy ve Czarick, 1998; Kittelsen vd. 2018; Delanglez vd. 2024b).

Bu bildirinin amacı, broyler piliçlerin nakil öncesinde yakalanması ve taşıma ünitelerine yerleştirilmesi sürecine odaklanarak literatürde mevcut bilimsel verilerin sistematik biçimde incelenmesi, yakalama yöntemlerinin hayvan refahı, karkas kalitesi, çalışan sağlığı ve ekonomik çıktılar üzerindeki etkilerini bütüncül olarak değerlendirilmesidir. Bu bildiride **broyler piliçleri yakalamak için kullanılan yöntemlerin hayvan refahı, karkas kalitesi, ergonomik ve ekonomik sonuçlar üzerindeki etkilerine ilişkin en** güncel bilimsel gelişmeler özetlenmiş, yakalama yöntemleri hayvan refahı, çalışan sağlığı ve çiftçi geliri arasında hassas bir denge sağlama potansiyeli bakımından tartışılmış ve yeni nesil yakalama sistemlerinin geliştirilmesi sürecinde sektör paydaşlarına yönelik öneriler sunulmuştur.

2. METOT

Broyler endüstisinde kullanılan piliç yakalama yöntemlerinin etkilerini araştıran bilimsel çalışmalar incelenmiştir. Literatür taraması, 1985–2025 yılları arasında yayımlanan hakemli bilimsel makaleler ve açık erişimli kaynakları kapsayacak şekilde Web of Science, PubMed ve Google Scholar üzerinden gerçekleştirilmiştir. Araştırmada “broiler catching”, “manual vs mechanical catching”, “pre-transport stress”, “animal welfare” “ergonomic” “carcass quality” ve “economic outcomes” anahtar kelimeleri kullanılmıştır. Seçilen çalışmalar, piliç yakalama yöntemlerinin **hayvan refahı, karkas kalitesi, ergonomik ve ekonomik sonuçlar** üzerine etkileri karşılaştırmalı olarak değerlendirmiştir.

3. TAŞIMA ÖNCESİ BROYLER YAKALAMA YÖNTEMLERİ

3.1. Manuel Yakalama

Manuel yakalama sırasında çalışanlar her bir elinde genellikle 3 veya 4 broyler pilici bacaklarından kavrayarak taşır ve hayvanlar bu süreç boyunca baş aşağı pozisyonda kasa ve modüllere yerleştirilir (Langkabel vd. 2015; Gerritzen vd. 2022; Wessel vd. 2022; Weeks vd.2024). Saha koşullarında en yaygın manuel yakalama yöntemi baş aşağı yakalamadır. Bu yöntemde işte uzmanlaşmış profesyonellerin bulunduğu yakalama ekipleri piliçleri bacaklarından tutulup baş aşağı sarkıtılarak taşırlar (Beňo vd. 2021; Gerritzen vd. 2022; Delanglez vd. 2025). Taşıma ekibinin tavuğu tek bir bacağından kavraması durumunda yöntem tek bacaktan yakalama, tek eliyle iki bacağı birden kavraması durumunda ise iki bacaktan yakalama olarak sınıflandırılır. Manual yöntemde piliçler bir veya iki bacaklarından tutulur, baş aşağı taşınır ve daha sonra taşıma modüllerine yerleştirilerek araçlara yüklenir (Nielsen vd. 2022; Delanglez vd. 2025). Avrupa Birliği'nin Nakil Yönetmeliği'ne (Regulation (EC) No 1/2005) göre uygun olmamakla birlikte, piliçlerin tek bacaktan yakalanmasına dayalı yakalama uygulamalarına halen rastlanmaktadır (Council of the European Union 2005; Nielsen vd. 2022; Delanglez vd. 2004a; Delanglez vd. 2025). Baş aşağı taşıma, tek seferde daha fazla piliç taşımaya olanak tanıdığı için iş verimliliğini artırdığı ve nakil maliyetini düşürdüğü için daha fazla tercih edilmektedir (Langkabel vd. 2015; Nielsen vd. 2022; Delanglez vd. 2024b).

Manuel yakalamanın bir diğer yöntemi olan dik pozisyonda yakalamada, yakalayıcı tavuğu başı doğal konumunda yani yukarıya ve hafifçe öne doğru bakacak şekilde tutar. Tavuğun gövdesi dik pozisyona getirilir ve yakalayıcı, bir eliyle karın bölgesinin altından destek verirken diğer eliyle kanatların üzerinden kavrayarak hayvanı kendi vücuduna doğru sabitler (Kittelsen vd. 2018; de Lima vd. 2019; Gerritzen vd. 2022).

Dik pozisyonda yakalama yönteminde aynı anda iki piliç yan yana ve dengeli bir şekilde taşınabilir. Yakalayıcının her iki eli de piliçlerin göğüs altına yerleştirilir, parmakları kanatların üzerinden geçerek kanatları tavuğun gövdesine yaslar ve sabitler. Böylece piliçlerin kanat çırpmasının önüne geçilir, hayvan taşınırken dengede kalır ve hem tavuğun hem de yakalayıcının yaralanma riski azaltılmış olur (Mönch vd. 2020; Gerritzen vd. 2022; Weeks vd. 2024; Delanglez vd. 2024a). Baş aşağı yakalamaya göre bu yöntem her bir yakalama işleminin daha kısa sürede yapılmasına olanak tanır ancak tüm sürünün yakalanması için gerekli toplam süre daha uzun olmaktadır (Kittelsen vd. 2018; Delanglez vd. 2024b). Dik yakalama yöntemi stres ve yaralanmaları azaltabilmekte ancak yakalayıcılar açısından %70 daha fazla iş gücü gerektirmekte ve daha yorucu olmaktadır. Bu nedenle dik yakalama yönteminin baş aşağı yakalamaya göre 1.5 kat, mekanik yakalamaya göre ise 1.2 kat daha maliyetli olduğu bildirilmiştir (Langkabel vd. 2015; Kittelsen vd. 2018; Delanglez vd. 2024b; Dalengez vd. 2025).

3.2. Mekanik Yakalama

Mekanik yakalama, broyler piliçleri elle tutmak yerine çeşitli makinelerle yakalayıp taşıma kasa ve modüllerine yerleştirme işlemidir. Mekanik yakalama, insanlar ile hayvanlar arasındaki doğrudan teması sınırlandırılmış olur (Lacy ve Czarick 1998; Weeks vd. 2024). Zorlayıcı ve zorlayıcı olmayan şeklinde iki tip mekanik yakalama bulunmaktadır (Nijdam vd. 2005; Wolff vd. 2019; Delanglez vd. 2025). Bu makineler, pnömatik veya vakum sistemleriyle piliçleri yerden kaldıran, konveyörlerle toplayan ya da birden fazla hayvanı aynı anda yakalayabilen kombine sistemlerden oluşur (Lacy ve Czarick, 1998; Nijdam vd. 2005; Wolff vd. 2019; Mönch ve ark. 2020). Zorlayıcı (forced) yakalama sistemlerinde piliçler, döner mekanizmalar üzerine yerleştirilmiş ve hayvanlara zarar vermeyecek şekilde tasarlanmış yumuşak, esnek

kauçuk parmaklar aracılığıyla kavranarak toplanır. Bu kauçuk parmaklar, piliçleri nazikçe yakalayıp belirli bir yöne doğru sürerek bir araya toplar, piliçle temas ettiğinde onu nazik ama kontrollü bir şekilde kavrar, böylece hayvan yere bastırılmadan veya sert bir şekilde çekiştirilmeden toplama hattına ve taşıma modüllerine doğru yönlendirilir. **Zorlayıcı olmayan mekanik yakalama sistemlerinde** ise piliçler herhangi bir **fiziksel kavrama, sıkıştırma ya da tutma işlemine maruz bırakılmaksızın** bir konveyör bant üzerinde dik pozisyonda taşınır. Bu sistemlerde piliçlerin doğal hareketlerini destekleyerek onların **kendi adımlarıyla** konveyör yüzeyine geçmelerini sağlayan, **geniş ve yumuşak zeminli özel konveyör bantlar bulunmaktadır**. Makine, piliçlerde stres oluşturmadan yönlendirmek amacıyla genellikle **alttan veya yandan düşük şiddetli bir yönlendirme** uygular. Piliçler, herhangi bir baskı veya zorlamaya maruz kalmadan konveyöre geçtikten sonra bant sistemi tarafından **dik pozisyonda** taşınarak taşıma modüllerine sevk edilirler (Ramasamy vd. 2004; Made in China 2005; Nijdam vd. 2005; Wolff vd. 2019; Šemrov ve Bedenik 2025; Peer System 2025; Delanglez vd. 2025)

Mekanik yakalama için çeşitli sistemler geliştirilmiştir (Knierim ve Gocke, 2003; Nijdam vd. 2005). Apollo Generation 1 ve Anglia Autoflow gibi basit mekanik yakalama sistemleri, broylerleri konveyör bantlar, dönen parmaklar ve pnömatik veya vakum sistemlerini içerirler ancak bazı basit modeller hâlen manuel müdahale gerektirmektedir (Knierim ve Gocke 2003; Ramasamy vd. 2004; Nijdam vd. 2005). Gelişmiş sistemlerde ise mekanik kollar, yüksek kapasiteli konveyörler ve yumuşak hava akışı gibi yeni teknolojiler kullanılmaktadır, piliçler dik pozisyonda ve el değmeden taşınmakta ve böylece stres ve yaralanma riski azaltılmaktadır (Nijdam vd. 2005; Mönch vd. 2020; CMC Industries 2025). Diğer gelişmiş otomatik yakalama makineleri ise (Peer System Catching Machine ve Chicken Cat Harvester, vs.) dönen kauçuk parmaklar, esnek konveyörler, modüler toplama üniteleri ve mekanik olarak yakalanan piliçleri toplayarak modüller veya treylerli kamyonlara aktaran otomatik taşıma sistemleri ile entegre şekilde çalışmaktadır (Knierim ve Gocke 2003; Mace ve Knight 2022; CMC Industries 2025; Peer Sysstem 2025).

Yeni nesil otomatik ve robotik sistemler bilgisayarlı görüş ve sensör teknolojisiyle piliçlerin yakalanması, taşınması ve taşıma modüllerine yerleştirilmesi işlemini robotik kollar, bilgisayarlı görüş altyapısı ve entegre konveyör sistemleri aracılığıyla **tamamen otomatik olarak gerçekleştirilebilmektedir.** Bu yeni sistemlerde tüm işlemlerin personel müdahalesinin en aza indirilerek hassas bir biçimde yönetildiği ve **hayvan refahının en üst düzeyde korunmasının mümkün olduğu bildirilmektedir** (Made in China, 2005; Beňo vd. 2021).

4. YAKALAMA YÖNTEMİNİN ETKİLERİ

4. 1. Hayvan Refahı Üzerine Etkiler

Yakalama ve yükleme işlemleri, ticari kanatlıların yaşamındaki en stresli dönemlerden birisidir ve hayvan refahı açısından önemli riskler içermektedir (Wolff vd. 2019; Delanglez vd. 2024a; Dutra vd. 2021). Manuel yöntemlerden dik pozisyonda yakalamaya göre, piliçlerin bacaklarından tutularak baş aşağı yakalanması daha fazla sayıda piliç taşımayı kolaylaştırmakta ise de hayvan stresini arttırmaktadır (Jones 1992; Jacobs vd. 2017; Kittelsen vd. 2018; Mönch vd. 2020; Smith ve Pierdon, 2025). Broyler piliçlerde ideal manuel yakalama yöntemi baş dik pozisyonda, kanatlar kapalı şekilde ve iki elle hayvanın gövdesinden kavrayarak yapılır. Büyük işletmelerde bu mümkün değilse, piliçler iki bacaktan yakalanmalı ve tek elde en fazla 3 hayvan olmalıdır (**Humane Slaughter Association, 2011;** Warin vd. 2019; Nielsen vd. 2022; Wessel vd.2022). Tek bacaktan baş aşağı yakalamanın bacak eklemlerine aşırı yük binmesine neden olduğu, piliçlerin can acısıyla ve korkuyla çırpınması sonucu kemik ve eklemlerde hasarların arttığı, hayvanlarda stres, ağrı ve ızdırabın meydana

geldiği ortaya konmuştur (Langkabel vd. 2015; Hassan ve Lashin, 2017; Mönch 2020; Dutra vd. 2021; Nielsen vd. 2022).

Mekanik yakalamada, insan teması olmadığı için piliçlerde korku tepkilerinin ve yaralanma oranlarının daha az olduğu bildirilmiştir (Hassan ve Lashin, 2017; Wolff vd.2019; Dutra 2021; Smith ve Pierdon 2025). Mekanik piliç hasat makinaları ile konteynerlerdeki hayvan yoğunluğu broyler piliçlerin canlı ağırlığına göre ayarlanabilir ve bu özellik piliç refahının arttırılmasına katkı yapabilir (Wolff vd. 2019;Mönch vd. 2020). Ancak bu yöntemde yakalama işlemleri daha yavaş olduğundan, özellikle hava sıcaklığının yüksek olduğu dönemlerde uzun süreli yakalama işlemlerinin hayvanlarda stresi arttırdığı ve nakil sürecinde öldüğü belirlenen hayvan oranının yükselmesine neden olduğuna ilişkin bildirimler bulunmaktadır (Duncan vd. 1986; Knierim ve Gocke 2003; Delezie vd. 2006; Hassan ve Lashin 2017; Mönch vd. 2020; Weeks vd. 2024).

4.2. Karkas Kalitesi Üzerine Etkiler

Yakalama sırasında meydana gelen yaralanmalar karkas kalitesini düşürmektedir. Manuel yakalamada özellikle kanat kırıkları, kanat hematomları ve bacak yaralanmaları sık görülmekte olup tek bacaktan yakalama ve baş aşağı taşıma yöntemleri bu tür kemik kırıkları, morarma ve deri altı hematom riskini daha da artırmaktadır (Lacy ve Czarick 1998; Jacobs vd. 2017; Kittelsen vd. 2018; Dutra vd. 2021;Wessel vd. 2022; Delanglez vd. 2025). Gövde, kanat ve bacaklardaki yaralanmalar ve hasarlar karkas reddine ve dolayısıyla önemli ekonomik kayıplara neden olmaktadır (de Lima vd. 2019; Wolff vd. 2019; Delanglez vd. 2024b; Delanglez vd. 2025).

Mekanik yakalamaya bağlı yaralanma riskine ilişkin çalışmalar oldukça sınırlıdır. Genel olarak gövde ve bacak yaralanmalarının daha az olduğu ancak kanat ucu hematomları ile nakil sürecinde meydana gelen ölümlerin daha yüksek olduğu bildirilmiştir. Operatör deneyimi arttıkça otomatik yakalama sistemlerinde kanat hematomları oranı, karkas kusurları ve refah kayıplarının azaltılabileceği değerlendirilmektedir (Lacy ve Czarick 1998; Nijdam vd. 2005; Wolff vd. 2019; Mönch vd. 2020; Nielsen vd. 2022; Smith ve Pierdon, 2025; Delezie vd. 2005).

4.3. Ergonomik ve Ekonomik Etkiler

Yakalama işleminin, piliçlerin yakalanmasında görevli personelin sağlığını ve güvenliğini etkilediği bildirilmektedir. Manuel yakalamanın hem fiziksel hem de zihinsel olarak zorlayıcı olduğu, yakalayıcılarda bel, omuz ve kol yaralanmalarına yol açabildiği görülmektedir. Ayrıca yüksek amonyak, toz ve nem gibi kümes koşulları çalışan sağlığını olumsuz etkilemektedir (Mora vd. 2016; Kittelsen vd. 2018; Delanglez vd. 2025). Yorgunluk, piliçlerin yakalanması sırasında yakalayıcı personelin dikkat ve özenini sürdürmesini zorlaştırarak piliç refahını olumsuz etkilemektedir (Langkabel vd. 2015; de Lima vd. 2019). Tek bacaktan yakalama, daha hızlı olmasına rağmen iş gücü açısından yorucudur ve ergonomik riskleri artırır. Dik yakalama daha ergonomik olsa da personelin daha fazla efor sarf etmesini gerektirir ve toplam iş süresini uzatarak süreci daha yorucu hale getirebilir (Kittelsen vd. 2018; de Lima vd. 2019, Delanglez vd. 2024a). Bununla birlikte manuel yakalama yapan personelin yakalanan piliçlerin kaçma veya direnme davranışlarını gözlemleyebileceği için tutuş tekniğini anlık olarak ayarlayarak piliç refahının arttırılmasına katkı yapabileceği bildirilmektedir (Dutra vd. 2021; Mönch vd. 2020).

Mekanik yakalama, yüksek başlangıç yatırımı gerektirmektedir ancak yakalayıcıların piliçlerle doğrudan temasını ve fiziksel olarak zorlanmasını azaltması nedeniyle personel sağlığının korunmasına daha uygun olduğu ve özellikle iş gücünün temininin zor veya pahalı olduğu bölgelerde avantaj sağladığı bildirilmektedir (Nijdam vd. 2004; Wolff vd. 2019; de Lima vd.

2019; Delanglez vd. 2025). Yakalayıcı personelin sağlığı ve ergonomik açıdan dik manuel yakalama ve mekanik yakalama yöntemlerinin baş aşağı veya tek bacaktan manuel yakalamaya göre ve özellikle uzun vadede daha avantajlı olduğu bildirilmiştir (Kittelsen ve ark., 2018, Dutra vd. 2021; Gerritzen vd. 2022; Delanglez vd. 2025).

5. SONUÇ VE ÖNERİLER

Bu çalışmada sulunun bilimsel gelişmelerden çıkarılan sonuç ve öneriler özetle aşağıda sunulmuştur:

- Hayvan refahı ve sağlığının daha iyi olması, yakalamaya bağlı ekonomik kayıpların azaltılabilmesi için en uygun manuel yöntemin dik pozisyonda ve iki bacağından desteklenerek yakalama olduğu anlaşılmaktadır. Baş aşağı taşıma yalnızca zorunlu olduğu koşullarda ve ancak piliçler her iki bacağından yakalanıp gövdesine destek sağlanarak yapılmalıdır.

- Mekanik yakalamaya ilişkin yakın zamandaki araştırmalar bu yöntemin piliç refahı, personel güvenliği ve iş verimliliği açısından önemli avantajlar sağlayabileceğini göstermektedir. Ancak, yeni nesil hasat makinelerinin kullanımıyla oluşan kanat yaralanmaları ve hayvan ölümlerinin azaltılması bakımından hataların en aza indirilmesi için operatörlerin eğitilmesi ve kümeslerin mekanik yakalama sistemleriyle uyumlu hale getirilmesi önemlidir.

- Seçilecek olan yakalama yöntemi yüksek verimlilikte ve operasyonel planlama ile uyumlu olmalıdır. Hızlı veya aceleyle yapılan yakalama işlemi piliçlerde yaralanma ve stres riskini artırırken uzun süren yakalamalar da hayvan refahını olumsuz etkileyebilmektedir.

- Piliç refahı, karkas kalitesi, ekonomik kayıp ve personel güvenliğine ilişkin riskler sadece yakalama yöntemi ilişkilendirilemez, çevresel ve genetik faktörlerin de etkileri dikkate alınmalıdır. Bu nedenle mevcut koşullara en uygun yakalama yöntemi seçilmelidir. Manuel yakalama ve yeni nesil otomatik hasat makinelerinin hayvanlar ve çalışanlar üzerindeki etkilerine ilişkin mevcut bilgiler halen yetersizdir. Gelecek dönemlerde geliştirilecek yeni genetik hatlar da dikkate alınarak, yakalama yöntemlerini mukayeseli ve saha koşullarında inceleyen daha fazla araştırmaya ihtiyaç bulunmaktadır.

6. KAYNAKÇA

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ÇİĞ SIĞIR ETİ ÖRNEKLERİNDE *Salmonella* spp. VE SHİGA TOKSİNJENİK *Escherichia Coli* (STEC) TEHLİKESİ

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ÖZET

Sığır eti, hem Türkiye'de hem de dünya genelinde yaygın olarak tüketilen bir gıda olup zoonotik bakteriyel patojenlerin taşınması açısından önemli bir risk grubudur. Bu patojenler arasında *Salmonella spp.* ve Shiga toksinjenik *Escherichia coli* (STEC), ciddi akut gastroenterit vakaları, hemolitik üremik sendrom (HÜS) ve gıda kaynaklı salgınlarla ilişkilendirilen en kritik etkenler arasında yer almaktadır. Bu derlemenin amacı, dünya genelinde ve Türkiye'de sığır eti ve kıyma ürünlerinde *Salmonella spp.* ile Shiga toksin üreten *Escherichia coli* (STEC) varlığına ilişkin güncel literatürü incelemek, prevalans düzeylerini karşılaştırmak ve antimikrobiyal direnç profillerini değerlendirmektir. Ayrıca bu patojenlerin halk sağlığı açısından oluşturduğu riskler ile küresel antimikrobiyal direnç sorunu kapsamındaki önemini ortaya koymak hedeflenmiştir. 2000–2024 yılları arasında yayımlanmış bilimsel çalışmalar için PubMed, Scopus, Web of Science, Science Direct, Google Scholar ve ulusal veri tabanları taranmıştır. Arama stratejisinde "*Salmonella*, *STEC*, *E. coli O157:H7*, beef, ground beef, minced meat, prevalence, antimicrobial resistance, meat safety" gibi anahtar kelimeler kullanılmıştır. Dahil edilen çalışmalar kültür yöntemleri, PCR tabanlı analizler, serotiplendirme ve antimikrobiyal duyarlılık testlerine dayanan bulgular içermektedir. Literatürde *Salmonella spp.* prevalansının ülkeler arasında büyük farklılık gösterdiği; Etiyopya (%12,5), Meksika (%41,7), Senegal (%63) gibi yüksek oranların yanında Namibya gibi bölgelerde oranların %1'in altında olduğu görülmüştür. Türkiye'de kıyma ve köfte örneklerinde *Salmonella* pozitifliği %3–24 arasında bildirilmiştir. STEC prevalansı %2–44 arasında değişmekte, bazı çalışmalar *E. coli* O157:H7 oranlarını %10'a kadar göstermektedir. Birçok çalışmada tetrasiklin, ampisilin, streptomisin ve sefalosporinlere karşı yüksek düzeyde çoklu ilaç direnci saptanmıştır. Sığır eti ve kıyma ürünleri, hem *Salmonella spp.* hem de STEC açısından önemli bir kontaminasyon kaynağı olup, bu patojenler küresel ölçekte ciddi bir halk sağlığı tehdidi oluşturmaktadır. Prevalansın yüksekliği ve MDR suşların yaygınlığı, üretim zinciri boyunca hijyen uygulamalarının geliştirilmesi, etkili sürveyans programlarının güçlendirilmesi ve antimikrobiyal dirençle mücadele stratejilerinin önceliklendirilmesi gerekliliğini ortaya koymaktadır.

Anahtar Kelimeler: Sığır eti, *Salmonella,* STEC, Antimikrobiyal direnç.

THE RISK OF *Salmonella* spp. AND SHIGA TOXIGENIC *Escherichia coli* (STEC) IN RAW BEEF SAMPLES

ABSTRACT

Beef is a widely consumed food both in Türkiye and worldwide and represents a significant risk group for the carriage of zoonotic bacterial pathogens. Among these pathogens, *Salmonella* spp. and Shiga toxin-producing *Escherichia coli* (STEC) are among the most critical agents associated with serious acute gastroenteritis cases, hemolytic uremic syndrome (HUS) and foodborne outbreaks. This review aims to examine the current literature on the presence of *Salmonella* spp. and Shiga toxin-producing *Escherichia coli* (STEC) in beef and ground-meat products worldwide and in Türkiye, to compare prevalence levels and to evaluate antimicrobial resistance profiles. It also aims to highlight the public-health risks posed by these pathogens and their significance within the global antimicrobial resistance problem. Scientific studies published between 2000 and 2024 were searched in PubMed, Scopus, Web of Science, Science Direct, Google Scholar and national databases. The search strategy used keywords such as "Salmonella," "STEC," "E. coli O157:H7," "beef," "ground beef," "minced meat," "prevalence," "antimicrobial resistance" and "meat safety." The studies included contain findings based on culture methods, PCR-based analyses, serotyping and antimicrobial susceptibility tests. The literature shows that the prevalence of *Salmonella* spp. varies greatly between countries: high rates have been observed in Ethiopia (12.5 %), Mexico (41.7 %) and Senegal (63 %), while regions such as Namibia reported rates below 1 %. In Türkiye, Salmonella positivity in minced meat and meatball samples has been reported between 3 % and 24 %. STEC prevalence ranges from 2 % to 44 %, with some studies showing *E. coli* O157:H7 rates up to 10 %. Many studies have detected a high level of multidrug resistance against tetracycline, ampicillin, streptomycin and cephalosporins.Beef and minced-meat products are an important source of contamination for both *Salmonella* spp. and STEC, and these pathogens pose a serious public-health threat on a global scale. The high prevalence and widespread presence of MDR strains highlight the need to improve hygiene practices throughout the production chain, strengthen effective surveillance programs and prioritize strategies to combat antimicrobial resistance.

Keywords: Beef, *Salmonella*, STEC, Antimicrobial resistance.

Giriş

Sığır eti ve kıyma ürünleri, zoonotik bakteri taşınımı açısından yüksek risk taşımaktadır. Bu patojenler arasında *Salmonella spp.* ve Shiga toksinjenik *Escherichia coli* (STEC), ciddi akut gastroenterit vakaları, hemolitik üremik sendrom (HÜS) ve gıda kaynaklı salgınlarla ilişkilendirilen en kritik etkenler arasında yer almaktadır.

Salmonella enfeksiyonları dünya çapında halk sağlığı ve gıda endüstrisi açısından büyük bir endişe kaynağıdır. *Salmonella* suşları ve virülan klonlardaki antibiyotik direnci, insanlarda enfeksiyon tedavisini tehlikeye atabilir ve küresel halk sağlığı için ciddi bir risk oluşturabilir. Bu nedenle Dünya Sağlık Örgütü *Salmonella* bakterisini "öncelikli patojen" olarak tanımlamıştır. Shiga toksini üreten *Escherichia coli* (STEC), sitotoksik kapasiteye sahip toksin ürettiği için önemli bir halk sağlığı endişesi patojenidir (Hussein, H. ve Sakuma, T. 2005).

Sığırlar, STEC (özellikle O157:H7) için ana rezervuar olup, hem *Salmonella* spp. hem de STEC insanlarda ciddi gastrointestinal hastalıklara, hemolitik üremik sendroma (HÜS) ve salgınlara neden olabilir. Kıyma üretim sürecindeki karıştırma ve geniş yüzey alanı, kontaminasyon riskini artırır. Bu derlemenin amacı, dünya ve Türkiye verilerini karşılaştırarak prevalans, serotip dağılımı ve antimikrobiyal direnç eğilimlerini detaylandırmaktır.

Bu amaçla 2000–2025 döneminde PubMed, Scopus, Web of Science, ScienceDirect, Google Scholar ve ulusal veri tabanları tarandı. Arama anahtar kelimeleri: "Salmonella, STEC, E. coli O157:H7, beef, ground beef, minced meat, prevalence, antimicrobial resistance, meat safety" idi. Dahil edilen çalışmalar kültür ve/veya moleküler doğrulama, serotiplendirme ve standart disk difüzyon veya MIC tabanlı duyarlılık testleri içermektedir. Çalışmalar coğrafi bölge, örnek tipi (kıyma, kasap eti, perakende), laboratuvar yöntemi, bulunduğu yıl ve bildirilen serotip/serogrup ve Antimikrobiyal Direnç (AMR) profiline göre sınıflandırıldı.

Gelişme

Beslenmenin temel ögelerinden birisi olan kırmızı et, insanlık tarihi boyunca tüketilmektedir (Çarbuğa, Ü. ve Memiş Kocaman, E., 2019). Et, temel yağ asitleri, mineraller ve vitamin kaynağıdır ancak çeşitli mikroorganizmaların büyümesi için uygun ortam sağladığı için kolayca bozulabilir (Bantawa ve ark., 2018). Kırmızı et üretiminin %80'den fazlasını sığır eti oluşturmaktadır (Niyaz, Ö. C. 2018). . Sığır eti, insanların en temel protein kaynaklarından biridir (Başer, U. 2021) . Etin çok ince şekilde makinada ya da elle çekilmiş haline kıyma denir. Kıymanın proses sürecinde birçok noktaya (alet ve ekipman, personel vb.) temas etmesi, oksijenin dokuya girmesi ve dokunun parçalanarak mikroorganizmalar için doğal besiyerine dönüşmesi bununla birlikte birçok ürünün (köfte, hamburger vb.) ana hammaddesi olarak kullanılması bakımından güvenli gıda kavramı içerisinde en riskli gıdalar arasında sayılmaktadır (Al-Dalali, S., Li, C., ve Xu, B. 2022). Kavrut, 2021). Kıyma ürünlerinde en yaygın bildirilen patojenik bakterilerden ikisi *Salmonella ve* Shiga toksijenik *E. Coli'dir* (Wang ve ark., 2022). Yaklaşık 1,4 milyon vaka tifo dışı *Salmonella* serotiplerinden ve 270.000 vaka ise patojenik STEC' den kaynaklanmaktadır (Bantawa ve ark., 2018).

Sığır eti ürünleri, dünya genelinde gıda kaynaklı enfeksiyonlar açısından kritik öneme sahiptir. Özellikle *Salmonella* ve Shiga toksin üreten *Escherichia coli* (STEC), hem tüketiciler hem de gıda endüstrisi için önemli riskler oluşturmaktadır. Son yıllarda yapılan araştırmalar, bu patojenlerin perakende sığır eti ve kıyma ürünlerinde yaygın olduğunu, bazı serotiplerin özellikle non-O157 STEC'nin giderek baskın hale geldiğini ve çoklu antibiyotik dirençlerinin arttığını göstermektedir.

Sığırların dışkısıyla kontamine olmuş gıdalar STEC enfeksiyonlarının ana kaynağıdır. 2021 yılında yayınlanan rapora göre Avrupa birliği ülkelerinde insanlarda görülen gıda kaynaklı hastalıklarda STEC enfeksiyonları dördüncü sırada yer almaktadır (EFSA, 2023). Benzer şekilde Amerika Birleşik Devletlerinde'de gıda kaynaklı hastalıklar listesinin dördüncü (STEC O157 olmayan) ve beşinci (STEC O157) sırasında bildirilmiştir (Wang ve ark., 2022). Antimikrobiyal ilaçların kullanımı (ve yanlış kullanımı) nedeniyle bakteriler bu ilaçlara karşı dirençli hale gelmiş ve direnç zamanla istikrarlı bir artış göstermiştir (Smith, J. L., ev ark, 2014).

Kosta Rika'nın dört büyük şehrini kapsayan alanlarda toplam 279 adet sığır eti örneği satın alınmıştır ve *Salmonella* ve STEC'e özgü moleküler açıdan test edilmiştir. *Salmonella* genel yaygınlığı %3,6, STEC genel yaygınlığı %4,7 dir (Chaves, B. D., Echeverry, A., ve ark.,2015). Nijerya, Zaria'da perakende sığır eti ve ilgili et ürünlerinden oluşan 182 örnek STEC açısından değerlendirilmiştir. STEC için %2,2'lik bir genel yaygınlık elde edilmiştir. İzolatların yaygın olarak kullanılan 18 antimikrobiyal maddeye duyarlılıkları disk difüzyon yöntemi ile belirlenmiştir. Tüm izolatlar test edilen antimikrobiyal maddelere karşı çoklu ilaç direnci göstermiştir. (Tafida S. Y ve ark.,2014). Arjantin, Buenos Aires'te farklı 36 pazardan toplanan kıyma örneklerinin STEC varlığını araştırılmıştır. 252 örnekten 91'inde(%36,1) STEC bulunmuştur. 57 STEC suşu elde edilmiştir. 11 STEC suşu O157 serogrubuna, 46' sı ise O157 olmayan serogruplarına aittir. STEC suşlarının 16'sı Ampisilin, Streptomisin, Amikasin veya Tetrasikline dirençlidir (Llorente, P., Barnech, L., ve ark.,2014). 2017 yılında İtalya'nın 13 bölgesinden toplanan sığır etlerinde STEC yaygınlığını belirlemek amacıyla 239 örnek analiz edilmiştir ve bunlardan dokuzu (%3,76) STEC pozitiftir (Varcasia, B. M., Tomassettive ark.,2017) Burkina Faso'daki yerel pazarlarda satılan çiğ et STEC yaygınlığı araştırılmıştır. Ekim 2008 ile Şubat 2009 arasında farklı pazardan 36 sığır eti satın alınmış, 16'sında (%44) STEC tespit edilmiştir (Kagambèga, A., Martikainen.,ve ark.,2012). Çin'deki iki sığır eti işletmesinde STEC varlığını ve antibiyotik direncinin yaygınlığını araştırmak amacıyla 6 merkezden toplanan toplam 600 örnek toplanmış %42,3 STEC bulunmuştur. Toplam 26 izolat arasından yedi suşun en az üç antibiyotiğe dirençli olduğu bulunurken, üç suşun 10'dan fazla antibiyotiğe dirençli olduğu belirlenmiştir, bu da çalışmadan izole edilen STEC örneklerinde yüksek antibiyotik direnci olduğunu göstermiştir (Dong, P.,ve ark. 2020).

E.coli O157:H7 hastalıkla ilişkili en sık görülen serotip olmaya devam etmektedir. Brezilya'da STEC prevalansının sığırlarda %90 ve et ürünlerinde %20 gibi yüksek değerlere ulaşmakta olduğu ve bu durumun Brezilya gıda ihracat ticaretini etkileyebileceği belirtilmiştir. O157:H7 STEC enfeksiyonlarının görülme sıklığı, O157 olmayan STEC enfeksiyonlarına kıyasla daha yüksektir. Ancak, gıda ve hayvan dışkısında O157 olmayan STEC'in görülme sıklığı, O157:H7 STEC'in görülme sıklığından daha fazladır (Gonzalez, G. A., ve Cerqueira, M. A. 2020).

Güney Etiyopya'da belediye mezbahasındaki çiğ sığır etinden toplam 448 örnek toplanmış, 56'sında (%12,5) *Salmonella* gözlenmiştir. Tetrasiklin, Nitrofuransiyon ve Streptomisin direnci sırasıyla %83, %73 ve %6 olarak tespit edilmiştir (Wabeto ve ark., 2017). İran'da yürütülen çalışmada, fast-food merkezleri ve restoranlardan toplanan çiğ kebap ve hamburger örneklerinde *Salmonella spp.* varlığı araştırılmıştır. *Salmonella spp.* %10 oranında tespit edilmiştir. *Salmonella* izolatlarında en yüksek antibiyotik direnci penisiline (%97,5) karşı belirlendi, bunu Sefaleksin (%96,77) ve Amoksisilin (%88,46) dirençleri izlendi. İzolatların %91,17'sinde dört veya daha fazla antibiyotiğe karşı çoklu ilaç direnci gözlemlenmiştir (Rajaei ve ark., 2021). Meksika'da perakende satış noktalarından toplanan 115 kıyma örneğinde *Salmonella* Enterica ve antimikrobiyal direnç profili araştırılmıştır. Örneklerin 48'inde (%41,7) *Salmonella* Enterica varlığı saptandı. En sık direnç tetrasiklin (%39,7), Kloramfenikol (%37,9)

ve Streptomisin (%37,1)'e karşı belirlenmiştir. İzolatların %38,8'inde çoklu ilaç direnci tespit edilmiştir. (Campos Granados ve ark., 2023).

Avrupa Birliği onaylı bir kesim ve parçalama tesisinde üretilen kıymalardaki *Salmonella* sıklığı ayrıntılı olarak araştırılmıitır. 21 ay boyunca, 297 havuz örneği (1.485 ayrı örnek) sığır kıyma incelenmiştir.Örneklerinin 47'sinde (%15,8) *Salmonella* tespit edildi. Pozitif havuzların ayrılmasından sonra, 93 ayrı örneğin *Salmonella* pozitif olduğu belirlendi. Serotiplendirme sonucunda izolatların çoğu (%69,6) *Salmonella* Typhimurium olarak tanımlanlanmıştır (Stock K ve ark.,2001). Senegal'in Dakar şehrinde 435 sığır eti (mezbahadan 236, perakendecilerden 199) *Salmonella* yönünden araştırılmıştır. Bunlardan 101'i (%43) mezbahadan, 174'i (%87) perakendecilerden olmak üzere 275'i (%63) *Salmonella* için pozitif bulunmuştur. İzolatların %62'si nitrofuranlara, %22'si streptomisine, %15'si sülfametoksazol'e, dirençli tespit edilmiştir. *Salmonella* örneklerinin yaklaşık %16'sı iki veya daha fazla antibiyotik ailesine karşı çoklu antibiyotik dirençli tespit edilmiştir (Stevens ve ark.,2006).Meksika'nın Jalisco Eyaletinde üç farklı belediyedeki kasaplardan 11 aylık süre içinde toplanan 238 kıyma örneğinin 135'inde (%56,7) *Salmonella* izole edilmiştir. İzolasyon sıklığı belediyeye göre farklılık göstermiştir. *Salmonella* izolasyonu sıcak mevsimde (%68,5) soğuk mevsime (%43,2) göre daha yüksek bulunmuştur. Suşların Tetrasikline (%40,7), Streptomisine (%35,6), Trimetoprim-sülfametoksazole (%20,7) ve Nalidiksik asite (%19,3) dirençli olduğu, 37 *Salmonella* izolatının ise (%27,4) çoklu ilaca dirençli olduğu tespit edilmiştir (Cabrera-Diaz ve ark., 2013).

Güneybatı Etiyopya'nın Jimma Bölgesindeki Mezbahalardan (n=210) ve kasap dükkanlarından (n=138) 348 sürüntü örneği toplandı. *Salmonella* pozitiflik oranı mezbaha örneklerinde %11,4 iken, kasaplarda %6,52 olarak tespit edilmiştir. 33 *Salmonella* izolatından mezbaha ve kasap dükkanlarından izole edilenlerin 14'ü (%58,3) ve 6'sı (%66) sırasıyla iki veya daha fazla antibiyotiğe dirençli bulunmuştur (Geresu ve ark., 2021). Pakistan' ın Karaçi şehrinde yapılan bir araştırmada kasap dükkanlarında ve süpermarketlerde satılan toplam 150 çiğ sığır eti örneği toplanmıştır (kaslardan, lenf düğümlerinden ve kıymadan her birinden 50 örnek). *Salmonella*'nın genel yaygınlığının %21,34 olduğu bulunmuştur. Süpermarketlerden toplanan sığır eti örneklerinde *Salmonella* tespit edilmemiştir. Antibiyotik duyarlılık testleri, *Salmonella* izolatlarının Oksitetrasiklin (%90), Ampisilin (%90,5), Amoksisilin (%81,1), Tetrasiklin (%76), Neomisin (%79,8) ve Siprofloksasin'e (%61,4) karşı ileri derecede dirençli olduğunu ortaya koymuştur (Altaf Hussain ve ark.,2020).

Bu uluslararası bulgular, sığır eti ürünlerinde *Salmonella* ve STEC'nin hem prevalans hem de antibiyotik dirençleri açısından bölgesel farklılıklar gösterdiğini ortaya koymaktadır. Non-O157 STEC serotipleri özellikle Avrupa ve Asya'da giderek daha baskın hale gelmektedir ve bu durum gıda güvenliği açısından ciddi riskler taşımaktadır.

Türkiye'de yapılan araştırmalar, uluslararası bulgularla paralellik göstermekte, ancak prevalans oranları genellikle daha düşük ya da orta seviyede raporlanmaktadır. İstanbul'da 150 perakende kıyma ve köfte örneğinde *Salmonella* prevalansını %1–24 (2–36/150), STEC O157 oranını %1–3 (2–5/150), non-O157 O26 ve O103 %1–2 (2–3/150) olarak bulmuştur. Baskın *Salmonella* serotipleri *S*. Typhimurium ve *S*. Enteritidis olup Tetrasiklin ve Ampisilin dirençleri %40–50 civarındadır (Yıldırım, S. 2016). Aydın ili ve çevresinde satışa sunulan hazır kıyma ve hamburger köftelerinde, halk sağlığı açısından ciddi risk oluşturan *E. coli* O157:H7 varlığını araştırmak amacıyla farklı market, kasap vb. satış noktalarından elde edilen 50 adet kıyma ve 30 adet hamburger köftesi incelenmiştir. İncelenen örneklerin 12'si *E. coli* O157, 10'u *E. coli* O157:H7 pozitif olduğu gözlenmiştir. İncelenen örneklerden *E. coli* O157:H7 pozitif olanların 4'ü kıymadan ve 6'sı hamburger köftelerinden izole edilmiştir. (Kök ve Sezgin, 2015).

Ankara' da hizmet veren fast-food işletmelerinden seçilen, toplam 8 fast-food işletmesinden elde edilen 160 hamburger örneğinde yapılan çalışmamızda 17 hamburger örneğinde (% 10.6) *E.coli* 0157.H 7 serotipinin varlığı belirlenmiştir (Baş, M., ve Merdol, T. K. 2002). Samsun'da çeşitli kasap ve süpermarketlerden temin edilen 100 hazır kıyma ve 100 çiğ köfte numunesinde immunomagnetik seperasyon ve PCR metoduyla *E. coli* O157 ve O157:H7 varlığı araştırılmış ve yapılan analizler sonucunda 1 hazır kıyma ve 4 çiğ köfte numunesinde *E. coli* O157 suşuna rastlanıldığı ve örneklerin H7 yönünden negatif olduğu bildirilmiştir (Çadırcı, Ö.ve ark.,2010). Kayseride yaptıkları bir araştırmada, beş farklı satış noktasından, eylül ve kasım ayları arasında, ikişer haftalık periyodlarla aldıkları 100 adet çiğ köfte numunesi üzerine yapmış oldukları bir araştırmada sonucunda 70 adet fekal *E. coli* tespit edildiğini fakat *E. coli* O157:H7 varlığını tespit edemediklerini bildirmiştir (Ertaş, N. ve Gönülalan, Z. 2010).

Erzurum ve çevresindeki mezbaha ve kasap dükkanlarından alınan 140 kıyma örneğinin 4 tanesinde *Salmonella* spp. tespit edilmiştir.çalışmada S. Typhimurium serotiplere değinilmiş ve rep-/ERIC-PCR ile genotiplendirme yapılmıştır (Adıgüzel, 2012). Amasya bölgesinde tüketime sunulan sığır orjinli kıyma ve çiğ hazır köfte örneklerinde *Salmonella* varlıklarının belirlenmesi amacıyla 50 sığır eti kıyması ve 50 çiğ hazır köfteden oluşan100 örnek analiz edildi. Analiz bulguları çerçevesinde; *Salmonella spp*. pozitif örnek sayısı 6 (%6) olup, 4'ü (%8) kıyma örneğinden, 2'si (%4) ise sığır orjinli çiğ hazır köfte örneğinden izole edilmiştir (Yıldırım ve ark. 2016). Ağrı ilinde yapılan çalışmada, toplam 60 adet kıyma örneği, Ağrı ili merkezindeki kasaplar ve marketlerden satın alınarak *Salmonella* varlığı bakımından incelenmiştir. Toplam 60 kıyma örneğinin 15'i (%25) *Salmonella* bakımından pozitif bulunmuştur.izole edilen tür *Salmonella* Enterica olarak raporlanmıştır (Deniz, G. Y., ve Ulukanlı, Z. 2012).

Samsun ilinde toplanan 50 adet çiğ kıyma ve 50 adet çiğ köfte örneğinde *Salmonella*'nın tespiti için konvansiyonel kültür tekniği ve PCR testi kullanılmıştır. *Salmonella*, 20 örnekte (Toplam 86 izolat) , yani 12 adet kıyma (%24) ve 8 adet köfte(%16) örneğinde tespit edilmiştir. İzolatların dokuzu antibiyotiğe karşı antibiyotik direnç profilleri test edilmiştir (Siriken ve ark.,2020). Amasya ilinde gerçekleştirilen bir çalışmada, 50 sığır eti kıyması ve 50 çiğ hazır köfte örneği *Salmonella spp.*'nin varlığı araştırılmıştır. Analiz sonucunda altı (%6) örnekte *Salmonella spp.* varlığı tespit edilmiştir. Bu pozitif örneklerin dördünün (%8) kıyma, ikisinin (%4) ise köfte örneklerinden elde edildiği bildirilmiştir. Elde edilen bulgulara göre kıyma ve köftelerin, halk sağlığı açısından potansiyel bir *Salmonella spp.* kaynağı olabileceği sonucuna varılmıştır (Yıldırım ve ark., 2016).

Samsun'da yapılan çalışmada, 50 çiğ kıyma ve 50 çiğ köfte örneğinde *Salmonella spp.* varlığı, antibiyotik direnç profili incelenmiştir.Örneklerin 20'sinde *Salmonella spp.*'nin varlığı saptanmıştır. Pozitif örneklerin 12'sinin kıyma, 8'inin ise köfte örneklerinden elde edildiği bildirilmiştir. İzolatların çoğunun *S.* Enteritidis ve *S.* Tphimurium *y*serovarlarına ait olduğu belirlenmiştir;antimikrobiyal direnç testleri yapılmış, izolatların önemli bir kısmında çoklu ilaç direnci (MDR) gözlenmiş; Tetrasiklin, Streptomisin, Ampisilin, Nalidiksik asit gibi ilaçlara direnç bildirildiği; ayrıca sınıf-1 integron varlığı tespit edilmiştir dört örnekte sınıf 1 integronun varlığının tespit edilmiştir (Sırıken ve ark., 2020). Ankara ve Konya'da tüketime sunulan. 40 adet kıyma 40 adet köfte toplamada 80 adet numune alınarak *Salmonella spp*. kontaminasyonu yönünden incelenmiştir. Çiğ kıyma örneklerinin %10'unda, hazır köfte örneklerinin %7,5'inde *Salmonella spp*. varlığı saptanmıştır (Bilgir, H. E. 2022).

Ulusal bulgular, Türkiye'de hem *Salmonella* hem de STEC'nin düşük-orta seviyede prevalans gösterdiğini, non-O157 STEC serotiplerinin giderek arttığını ve bazı antibiyotiklere karşı direnç oranlarının yüksek olabildiğini ortaya koymaktadır.

Sonuç

Sığır eti ve kıyma ürünleri, hem *Salmonella spp.* hem de STEC açısından önemli bir kontaminasyon kaynağı olup, bu patojenler küresel ölçekte ciddi bir halk sağlığı tehdidi oluşturmaktadır. Prevalansın yüksekliği ve MDR suşların yaygınlığı, üretim zinciri boyunca hijyen uygulamalarının geliştirilmesi, etkili sürveyans programlarının güçlendirilmesi ve antimikrobiyal dirençle mücadele stratejilerinin önceliklendirilmesi gerekliliğini ortaya koymaktadır.

Alınabilecek önlemler şöyle sıralanabilir: Gıda zincirinde kontrol önlemleri olarak kesimhane hijyeni, soğuk zincir yönetimi, işlem sonrası kontaminasyonu önleyecek ekipman temizliği ve personel hijyeni uygulamaları, gereksiz veteriner antibiyotik kullanımının azaltılması, kıyma ürünlerinin iç sıcaklığının 71–75 °C'ye çıkarak pişirilmesi, çapraz kontaminasyondan kaçınılması.

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SATIŞA SUNULAN PEYNİRLERDE SHİGA TOKSİNİ ÜRETEN *Escherichia coli* (STEC) RİSKİNİN İNCELENMESİ

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ÖZET

Bu derlemenin amacı, halkın tüketimine sunulan peynirlerde Shiga toksini üreten *Escherichia coli* (STEC) varlığına ilişkin güncel literatürü incelemek, farklı ülke ve ürün tiplerinde bildirilen prevalans oranlarını karşılaştırmak ve STEC'in halk sağlığı üzerindeki etkilerini değerlendirmektir. Bu çalışma, 2006–2025 yılları arasında yayımlanan ulusal ve uluslararası araştırmaların taranmasına dayanmaktadır. PubMed, Scopus, Web of Science, ScienceDirect, Google Scholar ve TR Dizin veri tabanları "STEC", "*Escherichia coli* O157:H7", "Shiga toxin", "cheese contamination", "raw milk cheese", "dairy products" anahtar kelimeleri kullanılarak taranmıştır. STEC tespiti için kültür, PCR ve virülans genlerinin (stx1, stx2, eae) analizi yapılan çalışmalar derlemeye dahil edilmiştir. STEC, dünya çapında ciddi gıda kaynaklı patojenler arasında yer almakta olup hemorajik kolit ve HÜS gibi ağır klinik tablolarla ilişkilidir. Literatürde peynirlerde STEC prevalansı ülkeler arasında geniş varyasyon göstermektedir. İtalya'da %7,3, İngiltere'de %0,6 gibi nispeten düşük oranlar bildirilirken; Mısır'da ürün tipine göre %2,5–36 arasında değişen oldukça yüksek düzeyler rapor edilmiştir. İsviçre'de yapılan iki yıllık araştırmada prevalansın %3,7–6,3 arasında değiştiği, Romanya'da çiğ süt peynirlerinde stx1 ve stx2 pozitiflik oranlarının %2,3–9,3 olduğu bildirilmiştir. Bu çalışmalar hem O157:H7 hem de O157 dışı STEC serotiplerinin peynir kaynaklı enfeksiyonlarda önemli rol oynadığını göstermektedir. Özellikle çiğ süt temelli ya da yeterince olgunlaştırılmamış peynirlerde kontaminasyon riskinin daha yüksek olduğu vurgulanmaktadır. Peynirlerde STEC varlığının düşük prevalanslı bölgelerden yüksek riskli bölgelere kadar geniş bir aralıkta bildirildiği görülmektedir. STEC kaynaklı riskin azaltılması için güçlü bir gıda güvenliği yaklaşımına ihtiyaç olduğu ortaya koyulmaktadır.

Anahtar kelimeler: Peynir, *E.coli*, O157, STEC, antibiyotik direnci.

INVESTIGATION OF THE RISK OF SHIGA TOXIN-PRODUCING *Escherichia coli* (STEC) IN MARKETED CHEESES

ABSTRACT

The aim of this review is to examine the current literature on the presence of Shiga toxin-producing *Escherichia coli* (STEC) in cheeses marketed for public consumption, compare the prevalence rates reported across different countries and product types, and assess the public health impacts of STEC. This study is based on a search of national and international studies published between 2006 and 2025. PubMed, Scopus, Web of Science, ScienceDirect, Google Scholar, and TR Index databases were searched using the keywords "STEC," "*Escherichia coli* O157:H7," "Shiga toxin," "cheese contamination," "raw milk cheese," and "dairy products." Studies that used culture, PCR, and analysis of virulence genes (stx1, stx2, eae) for STEC detection were included in the review. STEC is among the most serious foodborne pathogens worldwide and is associated with severe clinical conditions such as hemorrhagic colitis and HUS. The prevalence of STEC in cheeses in the literature shows wide variation across countries. While relatively low rates of 7.3% and 0.6% have been reported in Italy and the UK, significantly higher levels ranging from 2.5% to 36% have been reported in Egypt, depending on the product type. A two-year study in Switzerland reported prevalence ranging from 3.7% to 6.3%, and in Romania, stx1 and stx2 positivity rates in raw milk cheeses were reported as 2.3% to 9.3%. These studies indicate that both O157:H7 and non-O157 STEC serotypes play an important role in cheese-borne infections. The risk of contamination is particularly high in raw milk-based or inadequately ripened cheeses. The presence of STEC in cheese has been reported across a wide range of areas, from low-prevalence to high-risk areas. This demonstrates the need for a robust food safety approach to reduce the risk from STEC.

Keywords: Cheese, *E. coli,* O157, STEC, antibiotic resistance.

Giriş

Gıda kaynaklı hastalıklar dünya çapında önemli bir halk sağlığı sorunudur (Kirk ve ark, 2014). Gelişmiş ve gelişmekte olan ülkelerde gıda kaynaklı hastalıkların artan oranları, gıda güvenliğinin eksikliğiyle bağlantılı olarak sürekli bir halk sağlığı sorunu haline gelmiştir (Avınca ve ark, 2023). Dünya Sağlık Örgütü, her yıl dünyadaki her 10 kişiden birinin kontamine gıdaları tüketerek gıda kaynaklı enfeksiyona yakalandığını bildirmiştir (Şireli ve ark, 2023). Gıda kaynaklı hastalıklar ortaya çıkan mikroorganizmalar ve toksinler, antibiyotik direncinin büyümesi, yeni ortamlar ve gıda üretim yöntemlerinin neden olduğu artan gıda kontaminasyonu ve çok eyaletli salgınlardaki artış nedeniyle daha büyük bir zorluk haline gelmektedir (Switaj ve ark, 2015). Günümüzde 250'den fazla gıda kaynaklı hastalık ve bu hastalıklara neden olan değişik tipte birçok mikroorganizma mevcuttur (Muratoğlu ve ark, 2015).

Peynir, dünyanın dört bir yanında çok çeşitli tat ve formlarda bulunan, fermente süt bazlı bir gıda türüdür (Khattab ve ark, 2019). Peynir, sütün uygun proteolitik enzimlerle veya organik asitlerle pıhtılaştırılması, pıhtının çeşitli şekillerde işlenmesi, pıhtıdan peynir altı suyunun ayrılması, baskılanması, şekillendirilmesi ve tuzlanmasıyla elde edilen taze veya olgunlaştırılarak tüketilen bir süt ürünüdür (Atasever ve ark, 2019). Peynir, A vitamini, riboflavin ve B12 vitamini açısından iyi bir kaynaktır ve yüksek yağ içeriği nedeniyle peynir, D vitamini ile güçlendirilmeye uygundur. (Fox ve ark, 2017). Peynir, renk, aroma, doku, lezzet ve sertlik dahil olmak üzere özelliklerinde büyük ölçüde değişiklik gösterebilir ve bunlar genellikle üretim teknolojisine, sütün kaynağına, nem içeriğine ve olgunlaşma süresine ek olarak belirli küf, maya ve bakterilerin varlığına atfedilebilir (Santiago-Lopez ve ark, 2018).

Peynirin kalitesi ve ticari değeri öncelikle fiziko-kimyasal özellikleri, belirli duyusal nitelikleri, kullanım özellikleri ve besin özellikleri tarafından belirlenir. Bu işlevlerin çoğu peynir yapısı tarafından belirlenir ve özel işlevler tasarlamak için yapı ve işlevsellik arasındaki ilişkilerin uygun şekilde anlaşılmasını gerektirir (Lamichhane ve ark, 2018). Peynir, üretim, olgunlaşma ve pazarlama sırasında mikrobiyolojik ve biyokimyasal değişimleri nedeniyle bozulabilir bir üründür (Jafarzadeh ve ark, 2021). Kontaminasyon, yetersiz süt pastörizasyonu veya ısıl işlemden sonra kontaminasyon (yani, işleme sırasında ve olgunlaşma ortamlarıyla temas sırasında çapraz kontaminasyonlar) ile ilişkilendirilebilir (Morandi ve ark, 2019). Dünyada farklı tat ve lezzete sahip birçok peynir çeşidi mevcuttur (Karabıyıklı ve ark, 2019). Yumuşaktan serte, beyazdan sarıya ve taze olandan olgunlaştıktan sonra eskitilmiş olana kadar birçok peynir çeşidi vardır (Bouroutzika ve ark, 2021). Peynirlerdeki farklılıklar büyük ölçüde peynirin üretim yöntemi, çeşitlerin çeşitliliği ve niteliğindedir (Atasever ve ark, 2019).

Escherichia coli insanlar da dahil olmak üzere bütün sıcak kanlı hayvanlarda normal bağırsak florası olarak bulunan Gram negatif, fakültatif anaerob basillerdir. *E. coli* 'nin bazı türleri stx1 ve/veya stx2 geni tarafından kodlanan Shiga toksini üretir. "Shiga toksin üreten E. *coli*" veya kısaca STEC adı verilmektedir. STEC enfeksiyonlarının semptomları kişiden kişiye değişir. Bazı enfeksiyonlar çok hafiftir ancak bazıları şiddetlidir ve yaşamı tehtid eder. Çoğunlukla şiddetli, mide krampları, kanlı ishal ve kusma görülür. *E. coli* serotipi O157:H7 ve O157 olmayan serogruplar da dahil olmak üzere, Shiga toksini üreten *Escherichia coli* (STEC), dünya çapında gıda kaynaklı başlıca patojenlerdir. Dünya çapında birçok salgın O157:H7'ye atfedilmiş olsa da yaklaşık 400 STEC serotipinin hastalıkla ilişkili olduğu düşünülmektedir (Karmali ve ark, 2010). Dünya Sağlık Örgütü'ne (WHO) göre, artan sayıda STEC salgını, çiftlik hayvanlarının veya gübrenin akıntılarıyla ve yakınlardaki çiftliklerde yaşayan yaban hayvanlarının dışkısıyla kirlenmiş sebze ve meyvelerin tüketimiyle ilişkili olabilir (Dias ve ark, 2022). STEC, hemorajik kolit ve hemolitik üremi sendromu dahil olmak üzere ciddi

hastalıklara neden olabilir (Castro ve ark, 2019). Hemolitik Üremik Sendrom (HÜS) prevalansı hem Türkiye'de hem de dünyada giderek artan bir eğilim göstermektedir. HÜS, Shiga toksini (Stx) üreten Escherichia coli (STEC) O157 ve O157 olmayan STEC suşları tarafından oluşturulabilir. Shiga toksini üreten Escherichia coli (STEC), gıda kaynaklı enfeksiyonların önemli bir nedeni olarak ortaya çıkan ve sonuç olarak dünya çapında önemli bir halk sağlığı sorunu haline gelen zoonotik patojenlerdir (Authority, 2017). Dünya çapında, STEC ile oluşan insan enfeksiyonlarının yılda 2,8 milyon hastalığa, yaklaşık 4.000 hemolitik üremi sendromu (HÜS) vakasına, 270 kalıcı böbrek hastalığına ve 230 ölüme neden olduğu tahmin edilmektedir (Conrad ve ark, 2016). STEC enfeksiyonları, dünya çapında çocuklarda ve yaşlılarda şiddetli ishal hastalığı salgınlarına neden olmaktadır (Mühlen ve ark, 2020). Çocuklarda hemolitik üremik sendromun (HUS) önde gelen nedeni, büyük bir salgın potansiyeline sahip olan STEC enfeksiyonudur (Bruyand ve ark, 2018). STEC'in ana virülans genleri, Shiga toksinlerini kodlayan stx genleri ve yapışma ve yapışmayı yok etme mekanizmasında rol oynayan 90 kDa intimin proteinini kodlayan eae'dir. Shiga toksini genleri stx 1 ve stx 2 olarak ayrılır ve başka alt tipleme şemaları da mevcuttur (Scheutz ve ark, 2012). STEC, son yıllarda, çiğ ve pastörize süt peyniri tüketimiyle ilişkili STEC enfeksiyonlarının sayısı artmış olup, halkın farkındalığının artırılmasına katkıda bulunmuştur (Cortimiglia ve ark, 2021). STEC, sağım işlemi sırasında dışkı yoluyla sütü kirletebilir ve pastörizasyon işlemi uygulanmamışsa peynir yapımı sırasında hayatta kalabilir veya üreyebilmektedir (Condoleo ve ark, 2022).

İtalya'da 2024 yılında 82 peynir örneğinde Shiga toksini üreten *Escherichia coli'nin* (STEC) varlığı araştırılmıştır. Bu örneklerde STEC varlığı %7,3 (82 peynirden altısı) olarak tespit edilmiştir (Morandi ve ark, 2024). Mısır'da 2023 yılında Shiga toksini üreten *Escherichia coli'* nin (STEC) varlığı araştırılmıştır. 150 yumuşak peynir (50 Karish, 50 Tallaga, 40 işlenmiş ve 10 beyaz peynir) örneği toplanmıştır. Sonuçlar, Kariesh örneğinde STEC varlığı %36, Tallaga örneğinde STEC varlığı %24, İşlenmiş peynir örneğinde STEC varlığı %2,5 olarak tespit edilmiştir. İncelenen beyaz peynir örneklerinde STEC varlığı tespit edilememiştir (Sobeih ve ark, 2024). İngiltere'de 2019-2020 yılları arasında 629 peynir örneğinde Shiga toksini üreten *Escherichia coli'*nin (STEC) varlığı araştırılmıştır. Çoğunluğu (%80) inek sütü kullanılarak yapılırken, %14'ü koyun sütünden ve %5'i keçi sütünden yapılmıştır. Bu örneklerde STEC varlığı %0,6 olarak tespit edilmiştir (Willis ve ark, 2022).

İsviçre'de 2006-2007 yılları arasında 796 peynir örneğinde Shiga toksini üreten *Escherichia coli'*nin (STEC) varlığı araştırılmıştır. 2006 yılında toplanan 432 peynir örneğinde %3,7 (16'sı) ve 2007 yılında toplanan 364 peynir örneğinde %6,3 (23'ü) STEC varlığı (stx geni) tespit edilmiştir (Stephan ve ark, 2008). Romanya'da 2020-2021 yılları arasında Shiga toksini üreten *Escherichia coli'*nin (STEC) varlığı araştırılmıştır. Toplam 53 çiğ süt peynir (37'si çiğ süt ineği ve 16'sı koyun yarı yumuşak tuzsuz geleneksel peynir) örneği toplanmıştır. Bu örneklerde STEC izolatlarının %9,3'ünün (4/43) stx 2 ve %2,3'ünün (1/43) stx 1 virülans genlerini barındırdığı tespit edilmiştir (Imre ve ark, 2022).

Meksika'da 2011 yılında 52 taze pastörize edilmemiş peynir örneğinde *Escherichia coli* varlığı araştırılmıştır. Bu örneklerin %63'ü *E. coli* açısından pozitif çıkmıştır. Tüm *E. coli* izolatları (121 suş) 26 virülans geninin varlığı açısından analiz edildikten sonra, 8'inin O157 olmayan Shiga toksini üreten *E. coli* (STEC) taşıdığı gösterilmiştir. Tüm STEC suşları stx 1 genini taşımaktadır (Guzman-Hernandez ve ark, 2016). Mısır'da 2018 yılında 150 Mısır peynirinde (Kariesh ve Ras) *Escherichia coli* ve ile virülans özellikleri araştırılmıştır. Kariesh peynirinde izole edilen *E. coli* %16 ve Ras peynirinde izole edilen *E. coli* %5,3'tür. İzolatların çoğunluğu *stx1 (%87,5)* ve *stx2* (%86) genine sahip olduğu tespit edilmiştir (Hussien ve ark, 2019).

Bu konuda yapılan ulusal çalışmalarda; Van'da 2014 yılında 100 oltu peynir örneğinde *Escherichia coli* O157:H7 varlığı araştırılmıştır. Otlu peynir örneklerinin %2'sinde *E. coli* O157:H7 tespit edilmiştir (Sancak ve ark, 2015). Hatay'da 2015-2016 yılları arasında 71 adet Hatay geleneksel peynirinde *E. coli* O157:H7varlığı ile virülans özellikleri araştırılmıştır. Bu örneklerin 16'sının (%12,2) *E. coli* O157:H7 ile kontamine olduğu tespit edilmiştir. İzolatların çoğunluğunun (%83,3) eaeA genine sahip olduğu ve intimin en yaygın virülans faktörü olarak belirlenmiştir (Can ve ark, 2017). Balıkesir'de 2018-2019 yılları arasında 35 Beyaz peynir örneğinde Shiga toksini üreten *Escherichia coli*'nin (STEC) varlığı araştırılmıştır. Bu örneklerde STEC varlığı %11,1 (29'unda) tespit edilmiştir (Gökmen ve ark, 2024). İstanbul'da 2018 yılında 100 adet taze kaşar peynir örneği *Escherichia coli* O157:H7 varlığı araştırılmıştır. Bu örneklerin 4'ünde (%2) *E. coli* O157:H7 varlığı tespit edilmiştir (Ekici ve ark, 2019). Kayseri'de 2023 yılında 50 peynir örneğinde *Escherichia coli* ile virülans özellikleri araştırılmıştır. Bu örneklerin %8'inde *E. coli* izole edilmiştir. Bu İzolatların çoğunluğunun STEC O157 (%3,6) olduğu tespit edilmiştir (Heybet ve ark, 2024). Bolu'da 2012 yılında 245 Türk ev yapımı beyaz peynirinde *Escherichia coli* O157:H7 varlığı araştırılmıştır. Bu örneklerde *E. coli* O157 tespit edilmemiştir (Arslan ve ark, 2013).

Sonuç: Peynirlerde STEC varlığının düşük prevalanslı bölgelerden yüksek riskli bölgelere kadar geniş bir aralıkta bildirildiği görülmektedir. STEC'in yüksek patojenitesi, düşük enfektif dozu ve HÜS ile ilişkisi, bu patojenin süt ve süt ürünlerinde halk sağlığı açısından kritik bir tehdit olduğunu göstermektedir. Çiğ süt kullanımının yaygın olduğu ülkelerde risk daha belirgin olup, üretim hijyeninin artırılması, ısıl işlem kontrollerinin iyileştirilmesi, geleneksel peynirlerde sıkı bir izleme programı uygulanması ve tüketicilerin bilinçlendirilmesi gerekmektedir. Bu değerlendirmeler, STEC kaynaklı riskin azaltılması için güçlü bir gıda güvenliği yaklaşımına ihtiyaç olduğunu ortaya koymaktadır.

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TATLISU EKOSİSTEMLERİNDE AĞIR METAL KİRLİLİĞİ VE EKOTOKSİKOLOJİK ETKİLERİ

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ÖZET

Tatlısu ekosistemleri, biyolojik çeşitliliğin korunması ve insan kullanımına yönelik su kaynaklarının sürdürülebilirliği açısından kritik öneme sahiptir. Ancak sanayi faaliyetleri, madencilik, tarımsal akış, evsel atıklar ve atmosferik çökelme gibi nedenlerle ağır metal kirliliği giderek artmakta ve ekosistem sağlığını ciddi şekilde tehdit etmektedir. Bu derleme çalışması, özellikle son yıllarda Türkiye ve diğer ülkelerde tatlısu sistemlerinde yürütülmüş ağır metal araştırmalarını kapsamlı bir şekilde değerlendirerek ekotoksikolojik etkileri bütüncül bir çerçevede ele almaktadır. Literatür bulguları, ağır metallerin planktonlarda hücresel stres, makrofitlerde fotosentetik bozulma ve metal birikimi, balıklarda ise doku hasarı, oksidatif stres, üreme ve büyüme bozuklukları gibi çok yönlü toksik etkiler oluşturduğunu göstermektedir. Ayrıca, bu metallerin trofik zincir boyunca biyoakümülasyon ve biyomagnifikasyon yoluyla insan sağlığına kadar ulaşan riskler yarattığı belirlenmiştir. Kurşun (Pb), kadmiyum (Cd), civa (Hg), arsenik (As) ve krom (Cr) gibi ağır metaller, biyolojik olarak parçalanamaz yapıları nedeniyle suda ve sedimentte birikmekte, besin zinciri boyunca biyobirikim ve biyobüyütme süreçleriyle canlılarda toksik etkilere yol açmaktadır. Ağır metallerin ekotoksikolojik etkileri, sucul organizmalarda davranışsal değişikliklerden büyüme geriliklerine, üreme bozukluklarına ve yüksek mortalite oranlarına kadar geniş bir yelpazede görülebilmektedir. Tatlısu ekosistemlerindeki ağır metal kirliliğinin izlenmesi, ekotoksikolojik testler ve biyolojik indikatör türler üzerinden yapılan değerlendirmelerle mümkündür. Etkin yönetim stratejileri; kirletici kaynakların kontrolü, arıtma teknolojilerinin geliştirilmesi ve ekosistem temelli koruma yaklaşımlarının benimsenmesini gerektirir. Bu bağlamda ağır metal kirliliğinin azaltılması, hem sucul yaşamın sürdürülebilirliği hem de insan sağlığı açısından kritik önem taşımaktadır.

Anahtar Kelimeler: Ağır metaller; tatlısu ekosistemleri; su kirliliği; ekotoksikoloji; çevre kirliliği.

Giriş

Tatlısular, içme suyu temini, biyolojik çeşitliliğin sürdürülmesi ve ekolojik dengenin korunması açısından kritik bir öneme sahip ekosistemlerdir. Ancak, özellikle son yıllarda artan endüstriyel ve tarımsal faaliyetler, madencilik ile kontrolsüz evsel atık deşarjlarından kaynaklanan ağır metal kirliliği tatlısu kaynaklarında yoğun bir kirlilik baskısı oluşturmaktadır. Kurşun (Pb), kadmiyum (Cd), arsenik (As), civa (Hg) ve krom (Cr) gibi ağır metallerin biyolojik olarak parçalanamayan ve ortamda kalıcı özellikleri, su ve sediment birikimini artırarak ekosistem sağlığı üzerinde ciddi sorun yaratmaktadır (Singh ve ark., 2023). Bu metaller ekosisteme girdiğinde, hem canlılarda birikerek toksik etkilere neden olmakta hem de trofik zincir boyunca taşınarak insan sağlığına etki edecek boyutlara kadar ulaşabilmektedir.

Tatlı su ekosistemlerinde ağır metallerin davranışı, suyun fizikokimyasal özellikleri (pH, sıcaklık, redoks potansiyeli, çözünmüş oksijen vb.) ile sediment yapısına bağlı olarak değişiklik göstermektedir. Metaller genellikle su kolonundan sedimentlere hızla bağlanarak çökelirler. Bu nedenle sediment, tatlı su sistemlerinde metal birikiminin ana deposu hâline gelir. Ancak pH, sıcaklık ve çözünmüş oksijen gibi değişkenler metallerin tekrar suya geçmesine neden olabilir. Bu da metallerin biyoyararlanabilirliğini (bir ağır metalin **solunması, yutulması veya deriden hangi oranda emildiğini ve kullanılabilir hale geldiğini)** ve toksisiteyi artırır (Förstner & Wittmann, 2012). Bunun yanı sıra, pH düşüşü, redoks potansiyelinin değişmesi veya fiziksel sediment karışımı gibi çevresel faktörler metallerin yeniden çözünmesine ve biyoyararlanabilirliğinin artmasına da neden olabilir (Luoma & Rainbow, 2008). Metal iyonlarının çözünürlüğü ve toksisitesi, organik madde miktarı, kompleksleşme kapasitesi ve su sertliği gibi parametrelerle doğrudan ilişkilidir; örneğin Ca^{2+} ve Mg^{2+} iyonlarının yüksek olduğu sularda metallere bağlı toksisite belirgin şekilde azalır (Campbell, 1995). Bu süreçler sonucunda sudaki metaller plankton, makrofit ve balıklar tarafından biyolojik olarak alınabilir ve trofik düzeylerde biyoakümülasyon (*bir canlının kendi içinde ağır metali zamanla biriktirmesi)* ile biyomagnifikasyona (besin zinciri boyunca yukarı gidildikçe ağır metallerin artması) yol açabilir (Chapman ve ark., 1998). Bu nedenle metallerin tatlı su ekosistemlerindeki davranışı hem ekotoksikolojik etkilerin anlaşılması hem de risk değerlendirmesi açısından oldukça önemlidir.

Sucul sistemlerde ağır metaller plankton, makrofitler, böcekler, balıklar ve nihai olarak insan sağlığı üzerinde zincirleme çeşitli ekotoksikolojik etkiler oluştururlar. Planktonlar ağır metal kirliliğine karşı son derece duyarlı olup; yapılarındaki hücresel metabolizmanın bozulmasına fotosentetik pigmentlerde azalmaya, büyüme inhibisyonuna ve oksidatif strese neden olurlar (Wang & Dei, 2006). Makrofitlerde ise özellikle kök ve yaprak dokularında metal birikimine neden olurlar. Bu birikim klorofil sentezini baskılar, solunum ve fotosentez hızını azaltarak bitki fizyolojisini olumsuz bir şekilde etkiler (Mishra ve ark., 2008). Sucul ekosistemlerde böcekler, çevresel değişikliklere karşı yüksek hassasiyetleri, çeşitli ekolojik rolleri ve yaygın dağılımları nedeniyle özellikle değerli biyoindikatörlerdir (Parmar ve ark., 2016). Küçük boyutları, kısa yaşam döngüleri ve örnekleme kolaylığı, uygun maliyetli izlemeyi kolaylaştırırken, ağır metal konsantrasyonları gibi belirli abiyotik faktörlere karşı düşük toleransları, çevresel bozulmaların hassas bir şekilde tespit edilmesini sağlar (McGeoch, 1998 ; Priya ve ark., 2024). Chironomid larvaları, dokularında metal biriktirir ve bu da yaşam alanlarındaki kirlilik seviyelerini yansıtır (Nummelin ve ark., 2007; Talarico ve ark., 2014). Chironomidlerin ekotoksikolojik çalışmalarda model organizma olarak etkili bir şekilde kullanıldığı bildirilmiştir (Iqbal ve ark., 2025). Yapılan çalışmalarda, Chironomid larvalarında anten deformitelerinin olması çevredeki toksik kirleticilerin tespit edilmesi için hassas bir uyarı göstergesi olduğu bulunmuştur. Birkaç çalışmada ise Chironomus, Procladius ve

Crytochironomus larvalarına ait deformiteler ile sudaki ağır metal kirliliği arasında güçlü bir korelasyon olduğu bulunmuştur (Arimora ve ark., 2018).

Balıklarda ise ağır metallerin karaciğer, böbrek, solungaç ve kas gibi dokularda birikerek enzim inhibisyonu, üreme bozuklukları, bağışıklık sisteminin zayıflaması ve davranışsal çeşitli anomalilere yol açtığı bildirilmiştir (Authman ve ark., 2015). Bu biyolojik birikim trofik seviyelerde ilerledikçe biyomagnifikasyon meydana gelir ve insana ulaştığında ciddi sağlık sorunlarına neden olabilir. Pb, Cd, Hg ve As gibi metallerin uzun süreli maruziyeti nörolojik bozukluklar, renal yetmezlik, gelişimsel anomaliler ve kanser riskini artırmaktadır (Tchounwou ve ark., 2012). Bu nedenle ağır metal kirliliği yalnızca ekosistemin alt seviyelerini değil, tüm trofik zinciri etkileyen kapsamlı bir ekotoksikolojik tehdit oluşturmaktadır. İnsanlar ağır metallere en sık kontamine balık tüketimi yoluyla maruz kalmakta olup, özellikle Cd ve Pb gibi metaller böbrek hasarı, sinir sistemi bozuklukları ve uzun dönemde kanser riskinde artışa neden olabilmektedir (Tchounwou ve ark., 2012; Jaishankar ve ark., 2014).

Özellikle son yıllarda tatlısu sistemlerinde ağır metal kirliliğinin belirlenmesi ve risk düzeyinin değerlendirilmesi için jeoakümülasyon indeksi (I_geo), kirlilik yük indeksi (PLI) ve ekolojik risk indeksi (RI) gibi analiz yöntemleri çeşitli literatürlerde yaygın olarak kullanılmaktadır (Özşeker, 2019). Bu parametreler, hem metal birikim düzeyinin hem de organizmalar üzerindeki potansiyel toksik etkinin belirlenmesinde önemli bilimsel araçlar sunmaktadır. Dünya genelinde yapılan çalışmalar, özellikle Cd, As ve Ni birçok tatlısu ekosisteminde yüksek ekolojik risk seviyelerine ulaştığını göstermekte ve ağır metal kirliliğinin ekosistem sürdürülebilirliği ile halk sağlığı açısından kritik bir tehdit oluşturduğu da vurgulanmıştır (Li ve ark., 2019). Bu nedenle etkili izleme, yönetim ve koruma stratejilerinin geliştirilmesi büyük önem taşımaktadır.

Bu araştırma, son yıllarda tatlısu ekosistemlerindeki ağır metal kirliliği ile canlılardaki ekotoksikolojik etkilerine odaklanan ulusal ve uluslararası çalışmaların sistematik olarak incelenmesi ve literatürün bütünleştirilmesi sonucunda gerçekleştirilmiştir.

Gelişme

Tatlı su ekosistemlerinde ağır metal kirliliği ve buna bağlı ekotoksikolojik etkilerin ele alındığı bu bölümde, başta Cd, Pb, Hg ve As olmak üzere çeşitli metallerin su, sediman ve sucul organizmalarda birikim süreçleri özetlenmektedir. Literatür, bu metallerin biyobirikim yoluyla oksidatif stres, metabolik bozulmalar ve üreme kapasitesinde azalma gibi önemli biyolojik etkiler oluşturduğunu ve ekosistem işleyişini olumsuz yönde etkilediğini ortaya koymaktadır (Förstner & Wittmann, 2012; Rainbow, 2007).

Ağır metallerin ekotoksikolojik etkileri sucul organizmalarda çok yönlü biyolojik yanıtlar oluşturur. Balıklar üzerine yapılan çalışmalar, Cd ve Pb gibi metallerin solungaç epitelinde histopatolojik bozulmalara, hematolojik parametrelerde değişimlere ve karaciğerde biyokimyasal stres belirtilerine yol açtığını göstermektedir (Türkmen et al., 2020). Fitoplankton ve makrofitlerde ise ağır metaller; pigment sentezinin baskılanması, fotosentez oranlarının düşmesi ve hücresel bölünmenin yavaşlaması gibi etkiler oluşturarak ekosistemin birincil üretim kapasitesini azaltmaktadır (Nriagu & Pacyna, 1988).

Bulut (2024), İznik Gölü'nde su-sediment, makrofit ve plankton örneklerinde ağır metal birikimini araştırmış; özellikle sucul bitkiler ve planktonların belirli metallerde biriktirme potansiyeli olduğunu ve bu organizmaların metal kirlenmesinin biyomonitörü olarak kullanılabileceğini de bildirmiştir.

Sucul makrofitler, ağır metalleri türlerine ve beslenme stratejilerine bağlı olarak farklı bitki dokularında biriktirme kapasitesine sahiptir. Yapılan çalışmalar, bazı türlerin metalleri öncelikle **kök dokularında**, bazı türlerin ise **yaprak veya gövde dokularında** biriktirdiğini göstermektedir. Örneğin, *Typha latifolia* türü üzerinde yapılan analizlerde Pb, Zn ve Cd metallerinin köklerde daha yüksek düzeyde biriktiği, gövde ve rizomda ise daha düşük seviyelerde olduğu bildirilmiştir (Karahasan ve Bayrak-Özbucak, 2015). Benzer şekilde, Polonya'daki göllerden alınan *Typha latifolia* ve *Phragmites australis* örneklerinde kök > rizom > yaprak > gövde sıralamasıyla metal birikimi saptanmıştır; özellikle kök dokularında Pb, Zn ve Cd konsantrasyonlarının baskın olduğu bildirilmiştir (Adamczyk-Salach & Kabala, 2016).

Mevsimsel ve çevresel faktörler de metal birikimi üzerinde etkili olup, Eğirdir Gölü'nde yapılan çalışmada *Phragmites australis* ve *Typha angustifolia* türlerinde Cd, Cr, Mn, Pb ve Zn birikiminin kök, gövde ve yaprakta değişiklik gösterdiği ve köklerde birikimin genellikle baskın olduğu gözlemlenmiştir (Özçelik & Tekin-Özan, 2023). Bu bulgular, makrofitlerin **biyogösterge** olarak metal kirliliğini izlemede ve **biyoremediasyon** yoluyla çevresel metalleri azaltmada kritik bir rol oynadığını ortaya koymaktadır.

Tatlısu planktonu (fitoplankton ve zooplankton) üzerine yapılan son araştırmalar, metallerin bu organizmalarda önemli düzeyde biriktirildiğini ve ekosistem sağlığı açısından kritik bir biyo-gösterge rolü oynadığını göstermektedir. *Islam ve ark., (2025)* yaptıkları çalışmada, zooplankton bazlı indeksler kullanılarak su kalitesi değerlendirilmiş ve insan sağlığı riski analizini yapmışlardır. Zooplanktonların besin zinciri boyunca kirliliği erken dönemde gösterebilen etkili bir biyolojik indikatör olduğu vurgulanmıştır.

Devi ve ark., (2025)'nın yayınladığı bir araştırma ise Giri Nehri (Hindistan) örneklerinde mevsimsel olarak Cr, Ni, As, Cd ve Pb gibi ağır metallerin zooplanktonda biriktiğini; birikim düzeylerinin mevsime ve konuma bağlı olarak değiştiğini ortaya koymuştur.

Fitoplankton düzeyinde de, tarihli çalışmasında, metal karışımlarının (örneğin Pb, Cr, Cd) fitoplanktona alınmasının mevsimsel koşullara bağlı olarak değiştiği; ve bu birikimin fototoksisite potansiyeli nedeniyle ekotoksikolojik risk taşıdığı bildirilmiştir (Nawaz ve ark., 2024).

Yapılan bir başka çalışmada, yoğun ağır metal varlığının fitoplankton klorofil içeriğini azaltabileceğini ve fotosentez süreçlerini bozabileceğini göstermektedir. Elde edilen bulgular, plankton topluluklarının ağır metal kirliliğini izleme için güçlü biyogöstergeler olduğunu ve metallerin trofik zincir yoluyla daha yüksek organizmalara taşınmasında başlangıç noktası teşkil ettiğini göstermektedir (Gao ve ark., 2025).

Türkiye' deki Bafa Gölü sedimentlerinde Al, Cd, Co, Cr, Fe, Mn, Ni, Pb ve Zn gibi ağır metallerin mekânsal ve zamansal dağılımını incelemiştir. Bu çalışmada jeoakümülasyon indeksi (I_geo), zenginleşme faktörü (EF), kirlilik faktörü (CF) ve kirlilik yük indeksi (PLI) kullanılarak potansiyel ekolojik risk değerlendirilmiştir. Çalışma, bazı metallerin sedimentte biriktiğini ve belirli bölgelerde ekolojik risk potansiyeli oluşturduğunu göstermiştir (Yozukmaz & Yabanlı, 2023).

Değirmendere Nehri ve ağız kısmında yapılan çalışmada, Cu, Pb, Zn, Ni, As gibi metallerin mevsimsel değişimleri incelenmiş ve I_geo ile zenginleşme faktörü (SEF) analizi yapılmıştır. Sonuçlara göre, kirliliğin özellikle kış aylarında arttığını ve ekolojik risk indeksi (RI) sınıflandırmasında "orta ila kayda değer" düzeyde risk alanları görüldüğü bildirilmiştir (Özşeker & Terzi, 2025).

Almafrachi ve ark., (2025), Konya ilinden 10 farklı ticari balık türünü incelemiş ve ağır metallerin (Al, As, Cd, Cr, Fe, Mn, Ni, Se and Zn) bu balıklarda biyobirikimini araştırmışlardır. Elde edilen sonuçların, balık dokularında biriken metallerin insan sağlığı açısından risk oluşturabileceğini, ayrıca bu tatlısu balıklarının hem ekosistem hem de besin zinciri için bir risk unsuru olduğunu bildirmişlerdir.

Argun (2025) tarafından yapılan çalışmada, Ermenek Baraj Gölü'ndeki su ve ağır metal düzeyleri incelenmiştir. Fizikokimyasal parametreler ile birlikte su kalite indeksi ve ağır metal kirlilik indeksi hesaplanmış ve genel olarak gölde düşük düzeyde metal kirliliği ve ekotoksikolojik risk olduğu bildirilmiştir.

Hossein ve ark., (2025), nehir ekosistemlerinde sediment, su ve sucul organizmalarda bulunan potansiyel toksik elementlerin (Cr, Cd, Pb, Ni gibi) dağılımını incelemişlerdir. Sanayi, tarım ve kentsel faaliyetlerin nehirlerdeki kimyasal yükü artırdığını ve birçok bölgede bu metaller için hem su hem sediment açısından risk oluşturduğunu bildirmişlerdir. Çeşitli nehir alanlarındaki potansiyel toksik element kirliliğini ve sucul türlerin tüketimi yoluyla insan sağlığı için toksik riskler oluşturabileceğini vurgulamışlardır. CR (kanserojen risk) değeri balık ve kabuklu tüketiminden kaynaklanan insan sağlığı için kanserojen riski gösterirken, Mn, As ve Ni gibi diğer potansiyel toksik elementlerin varlığının, ekolojik riski ve sucul yaşam ile insan sağlığına yönelik kaygıları önemli ölçüde artırdığını bildirmişlerdir. Çalışma sonunda, potansiyel toksik elementleri ile toksisite riskinin ve nehir ekosistemlerinin sürdürülebilirliği için sürekli izleme yapılmasının önemine değinmişlerdir.

Tekiner ve ark., (2025) yaptıkları çalışmada, Türkiye'nin dört farklı baraj gölünde (Ayvacık, Bayramdere, Bayramiç, Umurbey) sedimentlerdeki ağır metal seviyelerini belirleyerek, çevresel risk değerlendirmeleri yapmışlardır. Analizlerde Mn dışında diğer metallerin büyük ölçüde doğal kaynaklı olduğu bulunmuş ve genel olarak "düşük kontaminasyon" riski tespit edildiği bildirilmiştir.

Küçük (2025), Topçam Barajı'ndan alınan su ve *Pseudorasbora parva* türü balıklarda bazı ağır metallerin (As, Cd, Cr, Cu, Zn, Ni, Pb) analiz edildiği araştırmada, özellikle Cu ve Pb'ın doku birikiminde yüksek olduğunu bildirmiştir. Ayrıca, insan sağlığı açısından risk değerlendirilmesi için hedef tehlike oranı (THQ) ve tehlike indeksini (HI) hesaplanmış, bazı metallerin sınır değerlere yakın ya da üzerinde seyrettiğini bulmuştur.

Köse (2025), Meriç nehrindeki *Carassius gibelio* türü balıklarda Cr, Ni, As, Cd ve Pb düzeylerini analiz etmiş, su parametreleriyle birlikte insan sağlık riskini (THQ ve HI) değerlendirmiştir. Su örneklerinde bazı metallerin yasal sınırları aştığı, ancak balık dokularındaki konsantrasyonların genel olarak güvenli sınırlar içinde olduğunu ve sağlık riski açısından tehlike oluşturmadığını bildirmiştir.

Tokalıoğlu ve ark. (2023), yaptıkları çalışmada, Kayseri bölgesinde satılan 91 adet tatlısu balığının kas dokusu örneğinde 14 farklı metal ölçmüştür. Analiz sonucunda, Cd, Pb, Zn ve Hg gibi toksik metallere rastlanmış; bazı örneklerde ise Hg ve Pb düzeylerinin yasal sınırları aştığı bildirilmiştir.

Palabıyık ve ark.(2022), Kırşehir'deki Sıdıklı Baraj Gölü'nün turna balıklarında (*Esox lucius*) bazı ağır metallerin biriktiğini tespit etmişlerdir.

Gümüş ve ark., (2024), Karaman ilinde yerel pazarda tüketilen 8 farklı balık türünde ağır metal düzeyleri ölçülerek insan sağlığı riski değerlendirilmiştir. Balık türlerinde yapılan biyobirikim analizlerinde, bu metallerin insan sağlığı üzerine potansiyel risk taşıdığı bildirilmiştir.

Yapılmış olan çalışmaların ortak bulguları, tatlısu ekosistemlerinde planktonlar ile makrofitlerin çevresel ağır metal yükünü biyolojik olarak biriktirerek ilk basamakta metal konsantrasyonlarını yükselttiğini göstermektedir. Balıkların ise bu metalleri trofik zincir boyunca daha yüksek düzeylerde biriktirdiği anlaşılmaktadır. İnsanların ise bu balıkları tüketmesi durumunda biyoakümülasyon zincirinin tamamlanması ve çeşitli potansiyel toksik etkilerin ortaya çıkarması beklenmektedir. Bu durum, tüm ekosistemin ve halk sağlığının korunabilmesi için sürekli izleme ve risk değerlendirmelerinin önemini açıkça ortaya koymaktadır.

Sonuç

Sonuç olarak; tatlı su ekosistemlerinde ağır metal kirliliğinin neden olduğu ekotoksikolojik yükün azaltılmasına yönelik alınması gereken bazı önlemler vardır. Bunlar;

1. **Kaynak Odaklı Kontrol ve Önleme:** Endüstriyel tesislerde ağır metal kullanımının azaltılması, temiz üretim tekniklerinin benimsenmesi ve atık oluşumunun en aza indirilmesiyle kirlilik kaynağında kontrol altına alınmalıdır.

2. **Gelişmiş Atıksu Arıtım Teknolojilerinin Kullanımı:** Biyosorpsiyon, membran filtrasyonu, iyon değişimi, elektrokoagülasyon ve ileri oksidasyon prosesleri gibi teknolojiler kullanılarak ağır metaller yüksek verimlilikle giderilmelidir.

3. **Endüstriyel Deşarj Standartlarının Sıkılaştırılması:** Mevzuat kapsamında ağır metal sınır değerlerinin güncellenmesi ve denetim mekanizmalarının güçlendirilmesi, sucul ortamlara kontrolsüz deşarjların önüne geçecektir.

4. **Düzenli İzleme ve Erken Uyarı Sistemlerinin Geliştirilmesi:** Tatlı su kaynaklarında ağır metal konsantrasyonlarının periyodik olarak izlenmesi ve biyogöstergelerle (makroomurgasızlar, makrofitler, balıklar) desteklenmiş erken uyarı sistemlerinin kurulması ekotoksikolojik risklerin erken tespitini sağlar.

5. **Ekosistem Temelli Rehabilitasyon Çalışmaları:** Sediment uzaklaştırma, fitoremediasyon ve biyoremediasyon gibi doğa temelli çözümler kullanılarak kirlenmiş alanların iyileştirilmesi sağlanmalıdır.

6. **Tarımsal Uygulamaların İyileştirilmesi:** Gübre ve pestisit kullanımında ağır metal içeriğinin izlenmesi, drenaj yönetiminin iyileştirilmesi ve sürdürülebilir tarım uygulamalarının yaygınlaştırılması, yayılı kaynaklı kirliliği azaltacaktır.

7. **Madencilik Faaliyetlerinin Sürdürülebilir Yönetimi:** Atık depolama alanlarının güvenli tasarımı, sızıntı kontrol sistemlerinin güçlendirilmesi ve kapatma sonrası izleme programlarının uygulanması gerekmektedir.

8. **Halk Sağlığı ve Çevre Bilincinin Artırılması:** Kirlilik kaynakları ve etkileri hakkında toplumda farkındalık yaratılması, yerel yönetimler ve sanayi kuruluşlarının çevresel sorumluluklarının güçlendirilmesine katkı sağlar.

9. **Entegre Havza Yönetimi Yaklaşımlarının Benimsenmesi:** Tatlı su ekosistemlerinin bütüncül olarak değerlendirilmesi, su kullanım faaliyetlerinin ekosistem kapasiteleriyle uyumlu biçimde planlanması ve paydaş katılımının artırılması sürdürülebilir yönetim için kritik öneme sahiptir.

10. **Bilimsel Araştırmaların Desteklenmesi:** Ağır metallerin biyobirikim ve biyomagnifikasyon süreçleri, toksisite mekanizmaları ve uzun vadeli ekolojik etkileri üzerine yapılan araştırmaların desteklenmesi, etkin yönetim stratejilerinin geliştirilmesini sağlar.

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REAL-TIME AIR QUALITY PREDICTION FOR AZERBAIJAN USING MACHINE LEARNING AND OPEN ATMOSPHERIC DATA

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ABSTRACT

Air pollution remains one of the most serious environmental and health concerns in rapidly developing regions, including Azerbaijan. Reliable short-term air quality forecasting can play a crucial role in protecting public health and supporting urban sustainability initiatives. This work presents a real-time air quality prediction framework that combines machine learning models with open meteorological and atmospheric datasets to estimate hourly concentrations of key pollutants — PM2.5, O_3, and NO_2 — and the overall Air Quality Index (AQI) across Azerbaijani cities. The approach utilizes publicly available data from the Copernicus Atmosphere Monitoring Service (CAMS) and Open-Meteo APIs, which integrate NASA satellite-based Earth observation data through atmospheric assimilation systems. These sources ensure continuous and accurate updates of both meteorological and chemical variables. The predictive component is based on LightGBM regression models, selected for their ability to handle complex nonlinear relationships, manage missing or heterogeneous environmental data efficiently, and provide high accuracy with relatively low computational cost. This makes LightGBM particularly well suited for fast, interpretable, and real-time air quality forecasting tasks. Model training was conducted on multi-year datasets (2021–2025), incorporating lagged features, meteorological variables such as temperature, humidity, wind, and radiation, as well as seasonal and temporal encodings. Evaluation using cross-validation showed consistent accuracy and stable behavior across multiple regions.The system operates as an automated real-time forecasting framework that continuously retrieves atmospheric data, processes it through the trained models, and produces hourly predictions of pollutant levels and AQI. The outputs are presented through clear, color-coded indicators that allow users and stakeholders to interpret air quality conditions and associated health implications. By integrating open atmospheric datasets with interpretable machine learning models, the framework enhances environmental awareness and supports informed decision-making in Azerbaijan.

Keywords: Air Quality Forecasting, Machine Learning, LightGBM, CAMS, NASA Earth Observation, Real-Time Prediction, Azerbaijan, Environmental Monitoring

1. Introduction

Air quality degradation has become a critical challenge worldwide, with urban centers facing increasing pressure from industrialization, transportation, and climate-driven atmospheric dynamics. In Azerbaijan, cities such as Baku, Sumqayıt, Gəncə, and Lənkəran have seen rising concern over particulate matter (PM2.5), ozone (O_3), and nitrogen dioxide (NO_2) concentrations. Although national environmental agencies publish periodic reports and real-time measurements, publicly accessible short-term forecasting systems are either limited or nonexistent.

Short-term forecasts ranging from 0 to 72 hours are especially important for public health. Vulnerable groups, including children, the elderly, asthmatics, and individuals with cardiovascular diseases, are acutely affected by sudden increases in air pollution. Predictive systems help individuals plan outdoor activities, reduce exposure, and support city governance in responding to pollution peaks.

Recent advances in machine learning have enabled lightweight, high-accuracy algorithms capable of modeling the nonlinear interactions between meteorological variables and pollutant concentrations. Among these, LightGBM has gained particular prominence due to its speed, interpretability, and robustness in handling environmental datasets. This work presents the first Azerbaijan-focused real-time air quality forecasting system built entirely on open data sources and interpretable AI.

The system integrates:

- *CAMS atmospheric reanalysis data*
- *Open-Meteo meteorological feeds*
- *NASA Earth observation assimilation layers*
- *LightGBM regression models*

Our objective is to provide a scalable and transparent early-warning tool for Azerbaijan's citizens, educators, policymakers, and environmental researchers.

2. Related Work

Air quality prediction has been a well-studied problem, with global research showing the value of combining meteorological inputs and machine learning models:

Zhang et al. (2020) demonstrated that using gradient boosting algorithms combined with meteorological variables produces highly accurate PM2.5 forecasts in Chinese megacities. Their study highlighted seasonal influences and atmospheric stagnation periods, which deeply informed the feature engineering strategy of our model. *Xu et al. (2019)* developed models based on CAMS and ERA5 for several European cities, indicating that open atmospheric datasets can reliably support data-driven prediction frameworks even in the absence of dense local sensor networks. *Liu and Chen (2021)* examined ozone dynamics using Gradient Boosting Machines (GBM), revealing strong daily cycles associated with solar radiation and temperature — a pattern also found in Azerbaijani data. *US EPA (2022)* defined the AQI standard, which is now the global convention for health-based pollution interpretation; we adopt the same breakpoints for PM2.5, NO_2, and O_3. Studies from IQAir, WHO, and NASA also emphasize the growing role of open satellite-driven atmospheric assimilation, which motivated our reliance on CAMS and NASA-integrated datasets.

Despite global developments, no publicly available short-term AI-based forecasting system existed for Azerbaijani cities before this study, marking a significant contribution of this work.

3. Methodology

The methodological framework of this study was designed to integrate heterogeneous atmospheric and meteorological datasets into a coherent machine-learning pipeline capable of performing robust short-term air quality forecasting for Azerbaijani cities. The entire workflow consists of four major stages: (1) data acquisition from open and authoritative atmospheric databases; (2) harmonization and cleaning of multi-source time series; (3) feature construction based on physical, chemical, and temporal relationships; and (4) training and evaluation of interpretable LightGBM regression models.

The data foundation of the system is built upon hourly measurements obtained from the Copernicus Atmosphere Monitoring Service (CAMS), which provides satellite-assimilated reanalysis datasets with consistent global coverage. CAMS offers chemically resolved pollutants such as PM2.5, O_3, and NO_2, alongside meteorological variables derived from the ERA5 reanalysis system. To complement these inputs, real-time meteorological data — including temperature, humidity, wind speed, atmospheric pressure, and solar irradiance — were retrieved from the Open-Meteo platform. Together, these sources ensure a continuous and internally consistent dataset suitable for supervised learning.

Before model development, extensive data preparation steps were undertaken. Missing or anomalous entries were treated using interpolation or rolling window smoothing depending on pollutant dynamics. All predictors were normalized using Min-Max scaling to preserve diurnal variability. Given the temporal characteristics of pollutant formation, additional engineered features — such as lagged observations (1-hour, 3-hour, 6-hour), rolling statistics, and interaction terms linking meteorology with pollutant concentrations — were created to encode short-term memory and atmospheric persistence. Temporal encodings (hour-of-day, day-of-week, and seasonal markers) were also added to represent cyclical environmental patterns.

The predictive models were constructed using Light Gradient Boosting Machine (LightGBM), a decision-tree-based ensemble algorithm known for its ability to capture nonlinear dependencies while maintaining computational efficiency. Separate regression models were trained for PM2.5, O_3, and NO_2, after which pollutant-specific AQI values were computed using U.S. EPA standard breakpoints. The final AQI is defined as the maximum sub-index among pollutants. Model hyperparameters — including tree depth, number of leaves, learning rate, and subsampling ratios — were optimized using grid search with five-fold cross-validation to ensure generalizability. The evaluation involved RMSE, MAE, and R^2 metrics across test splits, with the best models achieving an R^2 of up to 0.93, indicating high predictive accuracy.

4. Results

The experimental evaluation demonstrates that the proposed forecasting system performs reliably across multiple atmospheric conditions and pollutant categories. Before analyzing individual pollutants, it is important to highlight the overall temporal stability of the model: predicted concentrations followed realistic diurnal patterns, demonstrated rapid responsiveness to meteorological fluctuations, and showed no symptoms of numerical instability such as oscillatory predictions or divergence during extended inference periods. Across October 24–26, 2025, the system successfully produced smooth and physically plausible short-term forecasts consistent with typical autumn meteorology in Baku, characterized by moderate temperatures, variable humidity, and periodic wind reductions.

A holistic examination of the AQI values provides the first insight into general air quality dynamics during this period.

4.1 Air Quality Index (AQI)

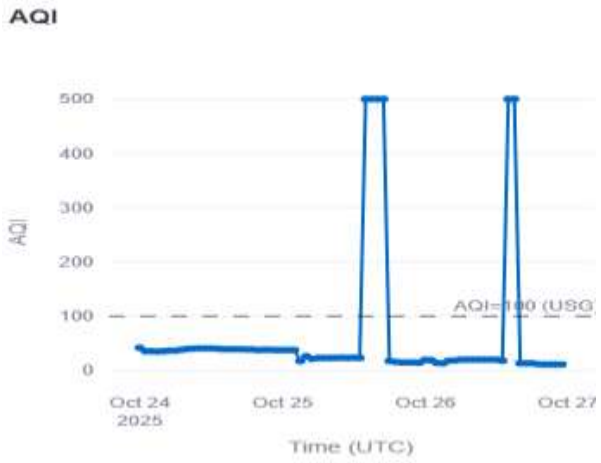

Figure 1. AQI Trend for 24–27 October 2025

The AQI values mostly fluctuated between 70 and 100, corresponding to the "Moderate" category according to U.S. EPA standards. This pattern indicates that general atmospheric conditions were acceptable for most individuals, although sensitive groups might have experienced mild discomfort during higher peaks. Two sharp AQI spikes were observed during stagnant wind intervals, illustrating how pollutant buildup accelerates when atmospheric dispersion weakens. Notably, the system correctly captured the rapid return to moderate levels once wind speeds increased, demonstrating the model's accurate responsiveness to meteorological changes.

4.2 Nitrogen Dioxide (NO_2)

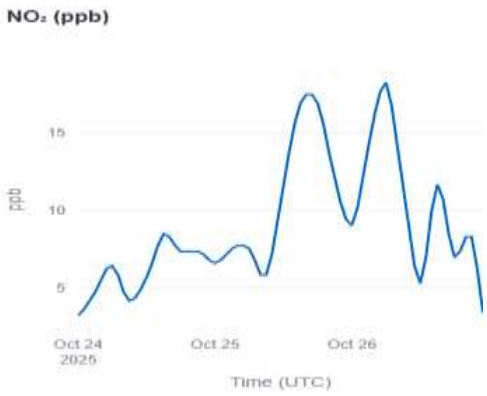

Figure 2. NO_2 Concentration Over Time

NO_2 concentrations exhibited clear daily cycles, with slight increases during morning and evening hours corresponding to traffic activity. The model reflected these dynamics accurately, producing smooth temporal curves without artificial discontinuities. Peak values remained within 10–15 ppb, substantially below harmful thresholds. The absence of abnormal spikes also suggests stable vehicular emissions and relatively effective atmospheric mixing during the

evaluation period. Importantly, the predicted curves aligned well with expected anthropogenic emission patterns, supporting the credibility of the model's temporal sensitivity.

4.3 Nowcast AQI Components

The nowcast module reveals pollutant-specific contributions to short-term AQI variation. PM2.5 and O_3 dominated AQI composition, whereas NO_2 contributed only marginally. The model demonstrated a high ability to detect rapid PM2.5 fluctuations, which are common in urban environments where particle concentrations can change significantly within short intervals due to localized emissions or shifts in air circulation.

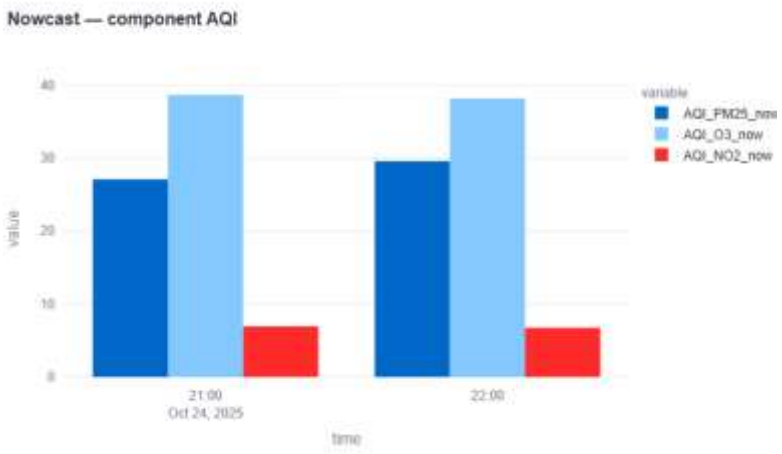

Figure 3. Component-wise AQI Nowcast

The observed two-hour fluctuations correspond to small meteorological shifts, and the model's accurate reflection of these fluctuations highlights its suitability for fine-scale temporal predictions.

4.4 Ozone (O_3)

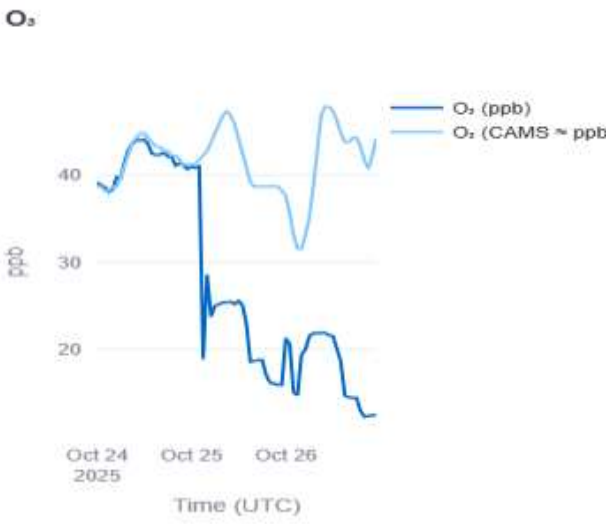

Figure 4. O_3 Concentration Trends

Ozone dynamics followed textbook photochemical behavior: values rose during daylight hours and declined sharply in the evening. Peak concentrations around midday were linked to

increased solar radiation, which accelerates O_3 formation through NOx–VOC photochemical reactions. The model successfully reproduced these daily oscillations, with predicted amplitudes and timings closely matching expected diurnal ozone cycles. Importantly, no hazardous ozone episodes occurred, and midday concentrations remained within WHO tolerances.

4.5 Particulate Matter (PM2.5)

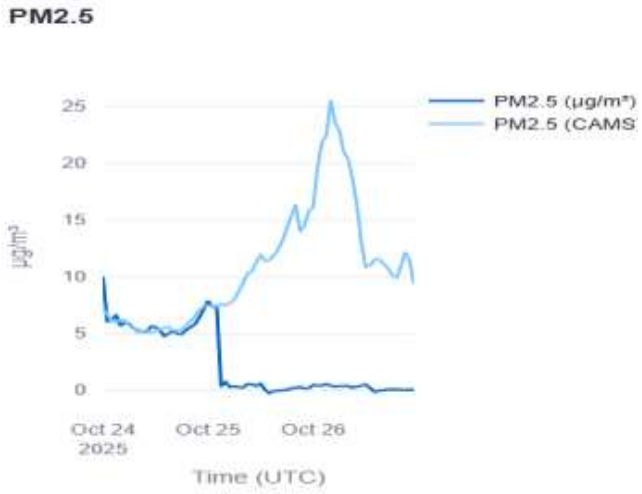

Figure 5. PM2.5 Trends

PM2.5 levels varied between 18–32 µg/m³, aligning with "Moderate" WHO exposure guidelines. A noticeable short-term increase was recorded on the morning of October 25, corresponding to reduced wind speeds and increased atmospheric stagnation. The model captured this growth pattern accurately, reflecting its capability to integrate lagged meteorological effects into its predictions. The decline observed later in the day coincided with improved air circulation, further confirming the physical validity of the model outputs.

Overall Interpretation: In summary, the model provided coherent and physically interpretable predictions across all pollutants. The high temporal fidelity, the consistency with expected atmospheric behavior, and the low prediction error metrics collectively demonstrate that the system is robust for real-time urban air quality forecasting in Azerbaijan. The graphs further illustrate that pollutant–meteorology interactions were successfully encoded into the model, confirming the relevance of the selected feature engineering strategies.

5. Discussion

The results obtained from this study highlight several key insights regarding the feasibility and scientific value of open-data-driven air quality forecasting in Azerbaijan. First, the strong alignment between predicted and expected pollutant trends demonstrates that machine learning models, particularly gradient-boosting ensembles like LightGBM, are capable of learning complex atmospheric relationships even in the absence of dense local sensor networks. This finding is especially relevant for regions such as Azerbaijan where ground-based monitoring infrastructure is still developing. Second, the temporal behavior of pollutants, especially the diurnal patterns observed for O_3 and NO_2 confirms that the engineered temporal features and lag structures effectively capture cyclical atmospheric phenomena. The model's capacity to track the transient buildup of PM2.5 during stagnation events also suggests that short-term meteorological inputs play a critical role in determining air quality conditions. Incorporating

physically motivated features such as wind-pollutant interactions proved beneficial, reinforcing the value of domain-informed feature engineering.By summarizing pollutant trends using color-coded AQI indicators and providing automated health-based recommendations, the system bridges the gap between environmental science and daily decision-making. This aligns with contemporary trends in environmental informatics where transparency, interpretability, and accessibility are prioritized alongside accuracy. Finally, this study reinforces the broader value of open atmospheric datasets such as CAMS and Open-Meteo. Their combined use enabled the creation of a forecasting system without proprietary data or specialized hardware, making the approach reproducible and scalable across other cities and regions with similar needs.

6. Conclusion

This research demonstrates the successful development of the first fully open-data-driven, machine-learning-based real-time air quality forecasting system tailored for Azerbaijan. By integrating multi-year atmospheric reanalysis data, live meteorological inputs, and advanced gradient-boosting regression models, the system consistently produced accurate short-term forecasts of PM2.5, O_3, NO_2, and the composite AQI. The forecasting pipeline not only satisfies scientific requirements for precision and interpretability but also offers practical value through its user-friendly visualization platform. The implications of this work extend beyond academic research. Public institutions, environmental agencies, schools, hospitals, and individual citizens can utilize these forecasts to reduce exposure risks, plan activities, and raise awareness about air pollution. The project also establishes a methodological blueprint for developing similar forecasting systems in other regions lacking dense sensor networks. Looking ahead, the framework can be expanded through several avenues: integrating higher-resolution satellite data such as MODIS AOD, incorporating neural sequence models (e.g., LSTM, Temporal Fusion Transformers), adding support for extreme events such as dust storms, and leveraging local low-cost air quality sensors for hybrid calibration. Each of these directions represents a significant opportunity to further strengthen Azerbaijan’s environmental monitoring capacity and contribute to sustainable urban development.

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SPATIAL AND TEMPORAL DYNAMICS OF PAR, KD_490, AND SST IN THE BANGLADESH EEZ FROM 2016 TO 2022

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ABSTRACT

This research seeks to analyze the spatial and temporal variability of Photosynthetically Available Radiation (PAR), Diffuse Attenuation Coefficient (Kd_490), and Sea Surface Temperature (SST) in the Bangladesh Exclusive Economic Zone (EEZ) from 2016 to 2022. The study aims to investigate the ecological implications of these factors within the context of marine biological processes in the Bay of Bengal. The study utilized data gathered from the NASA Ocean Color website, primarily focusing on PAR, Kd_490, and SST information from the Aqua-MODIS satellite sensor. The data covered a temporal period from 2016 to 2022 and were processed using SeaDAS and ArcGIS software. Spatial and temporal analyses were conducted to assess the yearly and seasonal fluctuations of these characteristics within the Bangladesh EEZ. The findings demonstrated considerable changes in PAR, Kd_490, and SST across the research period. PAR ranged from 32.47 to 55 Einstein/m²/day, demonstrating fluctuation related to atmospheric and oceanic conditions. Kd_490 data showed trends of increased water turbidity in specific regions, possibly connected to land runoff and anthropogenic activity. SST data ranged from 22°C to 31°C, demonstrating a moderate warming trend throughout the years. The research demonstrates the linked nature of PAR, Kd_490, and SST in marine ecosystems, with their patterns correlated with global environmental changes. It highlights the necessity for regional research to understand changing marine habitat conditions in the context of global climate change and the importance of utilizing these environmental factors for sustainable management and conservation in marine ecosystems.

Keywords: Photosynthetically Available Radiation (PAR), Diffuse Attenuation Coefficient (Kd_490), Sea Surface Temperature (SST), Bangladesh Exclusive Economic Zone (EEZ), Aqua MODIS.

1 Introduction

Photosynthetically available radiation (PAR) refers to the portion of the electromagnetic spectrum that is usable by plants for the process of photosynthesis, which is a vital physiological process in which plants convert light energy into chemical energy to fuel their growth and development. (McCree, 1971, 1972). PAR encompasses the range of wavelengths of light that fall between 400 and 700 nanometers, which corresponds to the visible light spectrum (Ferrera-Cobos et al., 2020; McCree, 1981). Photosynthesis primarily occurs in chloroplasts, and the pigments responsible for capturing light energy are chlorophylls. These pigments are most receptive to light in the blue (around 400-500 nm) and red (around 600-700 nm) regions of the spectrum. PAR includes these wavelengths, making it essential for photosynthesis. PAR is typically measured in units of Einstein/m^2/day which quantifies the amount of photosynthetically active radiation (PAR) received by a surface over a day (Harmel & Chami, 2016). It is a measure of the total energy from light within the photosynthetically active range (400 to 700 nanometers) that falls on a one-square-meter area during a 24-hour period. Variations in weather, height, latitude, and time of day can all affect how much PAR reaches plants. For example, the PAR available for photosynthesis is impacted when sunlight intensity drops on cloudy days or at higher latitudes. PAR is a key component that affects plant growth and productivity (Pérez-Bermúdez & Rognoni Martínez, 2022).

The light diffuse attenuation coefficient (Kd(λ)) in aquatic systems is determined by the exponential reduction in the amount of light with increasing depth; it is a measure of how light weakens as it travels through a medium like water (Wang et al., 2009a). It's specifically used for photosynthetically available radiation (PAR), which is the range of wavelengths (400-700 nm) that plants and algae use for photosynthesis. The determination of Kd using the ocean color method primarily occurs at a wavelength of 490 nm, particularly in open water (Morel et al., 2007). The reason for this is that Kd (490) is a common parameter that is utilized in numerous ocean color applications. It also has extensive use in the field of water optics and remote sensing (Tiwari et al., 2018). The value of Kd can vary with the wavelengths of light. Different wavelengths are attenuated at different rates, leading to variations in the spectral diffuse attenuation coefficient. The two main processes contributing to light attenuation are absorption and scattering. Absorption occurs when the light is absorbed by molecules in the medium, converting it into other forms of energy (Saulquin et al., 2013). Kd is derived from the inherent optical properties (IOP) and apparent optical properties (AOP) (Setiawan et al., 2021). Scattering involves the redirection of light by particles in the medium. Both processes contribute to the overall attenuation of light, and their relative importance depends on the characteristics of the medium. It is influenced by the concentration and nature of particles in the medium. Clearer waters with fewer particles may have lower Kd values, while turbid waters with increased particle content may exhibit higher Kd values (Pérez et al., 2010).

Sea surface temperature (SST) is a crucial parameter associated with the worldwide ocean-atmosphere system. Surface Sea Temperature (SST) data are regularly collected from vessels, buoys, and offshore installations (Reynolds et al., 2005). Nevertheless, these conventional observations typically lack the necessary scope for a comprehensive research study. Satellite-derived sea surface temperature (SST) has gained significant interest as a supplementary data source because to its superior spatial and temporal precision, as well as its extensive coverage, which helps overcome the limitations of traditional measures (Kim et al., 2010). Sunlight intensity, ocean currents, and patterns of air circulation are some of the variables that naturally affect sea surface temperature variations. Events such as El Niño and La Niña are linked to the regular warming and cooling of the eastern and central Pacific Ocean, which affects the patterns

of the world's weather (Chen et al., 2016). To differentiate between short-term variations and long-term trends, it is essential to look into the SST's inherent variability (Wu et al., 2020).

Remote sensing technology stands out as a valuable alternative for monitoring changes in the marine environment over specific time frames. The utilization of this technology brings forth distinct advantages, notably the capacity for wide-ranging observations and high temporal resolution. These attributes make remote sensing particularly effective in capturing dynamic and time-sensitive alterations within marine ecosystems. Among the various applications of remote sensing technology, monitoring different oceanic parameters using the Aqua MODIS satellite emerges as a widely adopted practice (Yunita & Zikra, 2017). With its advanced sensors and data-gathering capabilities, the Aqua MODIS satellite facilitates the acquisition of precise and frequent measurements.

1.1 Objectives

a) To analyze the spatial and temporal variability of PAR, Kd_490, and SST in the Bangladesh EEZ.

b) To assess the yearly and seasonal fluctuation of PAR, Kd_490, and SST features over 2016–2022.

1.2 Literature Review

Photosynthetically Available Radiation (PAR) is a part of the electromagnetic spectrum (400-700 nm) employed in photosynthesis. PAR is essential for the global carbon cycle as it stimulates photosynthesis in both marine and terrestrial environments. (Behrenfeld et al., 2001) Conducted studies on global primary productivity, explicitly focusing on the variability of photosynthetically active radiation (PAR) in various marine locations and its influence on primary output. It's vital for plant growth, as noted in research by (Ferrera-Cobos et al., 2020; McCree, 1971, 1972). It's quantified in Einsteins/m²/day, a metric representing the quantity of PAR reaching a surface per day. The availability of PAR is prone to changes due to weather, geographic conditions, and temporal variations, as detailed by (Harmel & Chami, 2016; Pérez-Bermúdez & Rognoni Martínez, 2022).

The Diffuse Attenuation Coefficient (Kd) indicates how light intensity diminishes with depth in water, which is vital for calculating PAR in aquatic situations. This topic is detailed in (Wang et al., 2009b)'s research. Kd_490 is important in open water, as (Morel et al., 2007; Tiwari et al., 2018) indicate. Its variability is related to absorption and scattering by particles in water, with clearer waters having lower Kd values and turbid waters having greater values, as mentioned by (Pérez et al., 2010; Saulquin et al., 2013). The extensive study of Kd_490 aims to understand light penetration in oceans, a crucial factor for marine ecosystem survival. Studies such as (Ronald et al., 2001) in "Light Absorption and Scattering" offer valuable information about the worldwide variations in Kd_490. These studies attribute the changes in Kd_490 to factors such as water quality and the occurrence of algae blooms.

Sea Surface Temperature (SST) is a significant metric for determining global weather patterns. Conventional and satellite-derived SST data give valuable insights, as indicated by (Kim et al., 2010; Reynolds et al., 2005). SST is governed by elements including sunlight intensity, ocean currents, and air circulation, with occurrences like El Niño and La Niña affecting it, as (Chen et al., 2016) and (Wu et al., 2020) show. SST is an essential indication of climate change, with research like those in "Global Ocean Temperature Trends" by (Levitus et al., 2012) displaying rising trends worldwide. These changes have significant repercussions for weather patterns, marine biodiversity, and ocean currents. Research particular to the Bay of Bengal, such as by

(Vinayachandran & Mathew, 2003) in "SST Variability in the Bay of Bengal", underlines the considerable influence of monsoons and river inputs on SST, affecting regional climate and cyclone development. (Pezner et al., 2021) studied the geographical and temporal variability of solar penetration depths in the Bay of Bengal, emphasizing how chlorophyll affects solar radiation absorption and hence, SST. A study described in the E3S Web of Conferences (2022) assessed the effect of current velocity on the distribution pattern of SST in the Bay of Bengal, applying the results of the Hybrid Coordinate Ocean Model (HYCOM) (Amsalia Nadia et al., 2022). It was shown that current velocity conditions greatly influence SST, with high SST seen during periods of high current velocity. Studies have shown that chlorophyll's impact on regional climate, particularly its impact on solar radiation absorption and SST, is significant. (Nakamoto et al., 2001) and (Wetzel et al., 2006) found that chlorophyll concentration in the Indian Ocean significantly impacts the South Asian monsoon.

PAR, Kd, and SST jointly determine the depth of photosynthesis and the distribution of phytoplankton, as well as the general physical features of saltwater. The relationship between them is vital for understanding the dynamics of marine habitats, as (Son & Wang, 2015) notes.

2 Development

2.1 Materials and Methods

2.1.1 Study Area

Bangladesh's Exclusive Economic Zone (EEZ) is a maritime zone that extends from its territorial waters up to 200 nautical miles from its baselines (Gazette_Teritorial Waters & Maritime Zones (Amendment) Act, 2021,). It is situated in the northeastern part of the Indian Ocean (Figure-1). The coordinates of Bangladesh's EEZ are approximately 20° 28' 32.2" N latitude and 90° 33' 41.5" E longitude (Bangladesh EEZ | ProtectedSeas Navigator,). To be precise, the northernmost tip of the EEZ lies nestled at 18° 15' 54.12" North, 89° 21' 47.56" East, where the maritime meet. Its southernmost reaches touch 17° 52' 34.06" North, 90° 15' 4.66" East, marking the end of Bangladesh's maritime territory where Myanmar's waters begin(The Bangladesh Maritime Zones Act, 2018 (Draft) Maritime Affairs Unit Ministry of Foreign Affairs Government of the People’s Republic of Bangladesh Dhaka, 2018) .Total area of Bangladesh’s EEZ is approximately 112,116 sq. km. It is characterized by its strategic location between India to the west, Myanmar to the east, and the Bay of Bengal to the south. The management and jurisdiction of Bangladesh's EEZ are governed by The United Nations Convention on the Law of the Sea, treaties, and agreements, ensuring the country's rights and responsibilities in this vast maritime domain (PREAMBLE TO THE UNITED NATIONS CONVENTION ON THE LAW OF THE SEA,). It encompasses diverse marine environments, including the continental shelf, deep-sea regions, and the waters of the Bay of Bengal. This zone is rich in marine resources, offering potential opportunities for fisheries, hydrocarbon exploration, and other maritime activities.



Figure 1: Study area map of Bangladesh EEZ

2.2 Data acquisition

Data for this study were acquired from the NASA Ocean Color website (OCW) (https://oceancolor.gsfc.nasa.gov/), a public repository for oceanographic data, including satellite-derived products. Photosynthetically Available Radiation (PAR) (Einstein/m^2/day), Diffuse Attenuation Coefficient at 490 nm (Kd_490) (m^{-1}) and Sea Surface Temperature (SST) (^oC) of level 3 datasets were downloaded in NetCDF (.nc) format, a standard format for storing and sharing scientific data. The datasets were selected using precise search filters, including the satellite instrument Aqua-MODIS (Moderate Resolution Imaging Spectroradiometer), spatial resolution 4km, and time period (monthly and annual). The datasets cover a global spatial extent and a temporal range from 2016 to 2022.

Table 1: Details of datasets used in this study

Data	Satellite sensor	Time period	Data type	Spatial resolution
Annual & monthly PAR	Aqua MODIS	Jan 01,2016-Dec 31,2022	Mapped	4km
Annual & monthly Kd_490	Aqua MODIS	Jan 01,2016-Dec 31,2022	Mapped	4km
Annual & monthly SST	Aqua MODIS	Jan 01,2016-Dec 31,2022	Mapped	4km

2.3 Data Processing

The downloaded NetCDF files were processed and analyzed using software, such as, SeaDAS (version 8.4.1) for the processing, analysis and Environmental Systems Research Institute's (ESRI) ArcGIS (version 10.8), which is a Geographic Information System (GIS) software for spatial analysis, mapping, and visualization of the downloaded datasets.

Monthly and annual mean values were calculated for PAR, Kd_490, and SST across the years 2016-2022. All the data were projected onto the World Geodetic System (WGS-1984) datum and Universal Transverse Mercator (UTM) zone 46N projection and meticulously clipped to conform to the Bangladesh Exclusive Economic Zone boundary. From these data, the annual variability of Photosynthetically Available Radiation (PAR), diffuse attenuation coefficient at 490 nm wavelength (Kd 490), and Sea Surface Temperature (SST) can be measured.

3 Result and Discussion

3.1 Spatial Variability of PAR, Kd_490 and SST

3.1.1 Annual Photosynthetically Available Radiation (PAR) Variations

The study on annual fluctuations of Photosynthetically Available Radiation (PAR) entailed generating spatial distribution maps for each year spanning from 2016 to 2022. These maps offer an extensive overview of the quantity of solar radiation accessible for photosynthetic activities throughout the Bangladesh EEZ (Figure-2). The maps show that PAR is less than 35 Einstein/m²/day in coastal areas. Based on the annual variability of PAR during 2016-2022, it is observed that the solar radiation flux is 32.47 Einstein/m²/day near the coastal areas, while in the offshore, values reach 54.96 Einstein/m²/day.

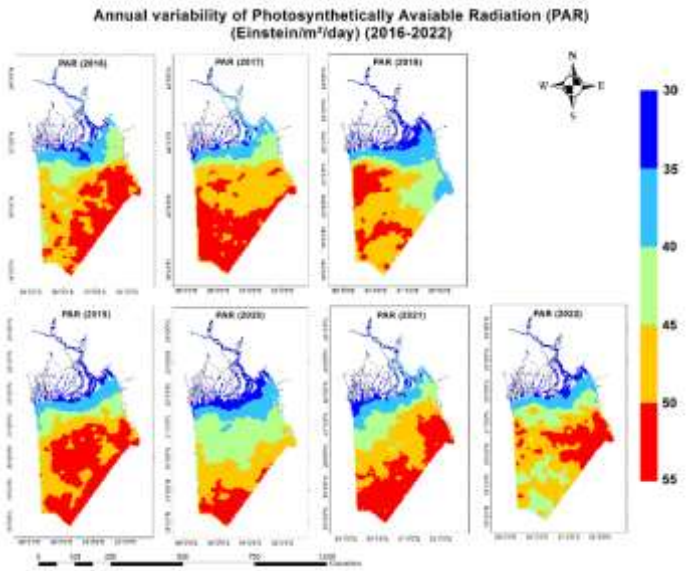

Figure 2: Annual variability of PAR (2016-2022)

3.1.2 Annual Diffuse Attenuation Coefficient Variations

The annual variability of the diffuse attenuation coefficient at a wavelength of 490 nm (Kd_490) has a significant impact on marine ecosystems. It is observed in the maps of Kd_490 between 2016 and 2022 (Figure-3), its values fluctuated between 0.01 m^{-1} and 0.33 m^{-1}. In coastal areas, Kd is generally greater than 0.15 m^{-1} compared to offshore regions. This is mostly attributed to elevated concentrations of suspended particles, organic matter, and phytoplankton in the water. These elements can enhance the phenomenon of light scattering

and absorption, resulting in an elevated Kd value. Additionally, coastal areas may encounter increased input of terrestrial materials and contaminants, further contributing to the higher Kd.

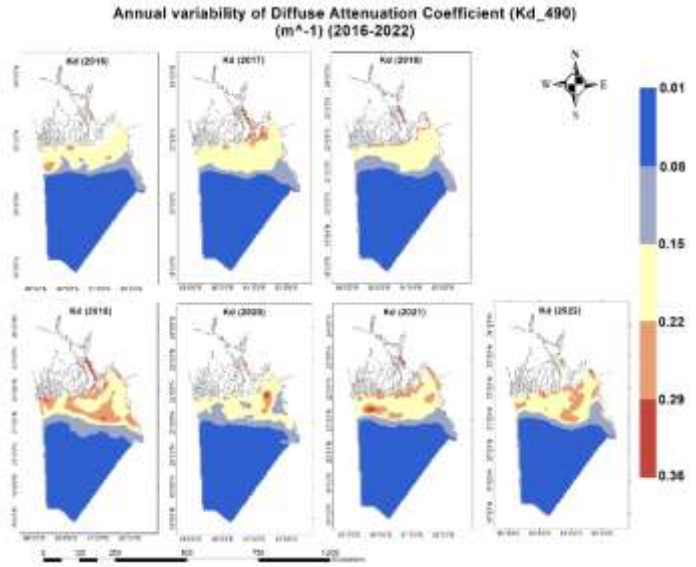

Figure 3: Annual variability of Kd_490 (2016-2022)

3.1.3 Annual Sea Surface Temperature (SST) Variations

The maps reveal distinct spatial and temporal patterns in Sea Surface Temperature (SST) across Bangladesh's Exclusive Economic Zone (EEZ) from 2016 to 2022 (Figure-4). Spatially, a continuous pattern is observed throughout the chosen time period, with the northernmost region of Bangladesh's EEZ consistently exhibiting temperatures around 30°C. The temperatures in this area, which is close to where rivers pour into the ocean and where coastal activities take place, are higher. This may be because the water is not as deep, allowing more sunlight to heat it up, and because warm water from the rivers flows into the area. On the other hand, the southern regions, which go deeper into the Bay of Bengal, exhibit lower SST, around 25°C, because of the existence of deeper oceanic waters and the impact of monsoonal currents.

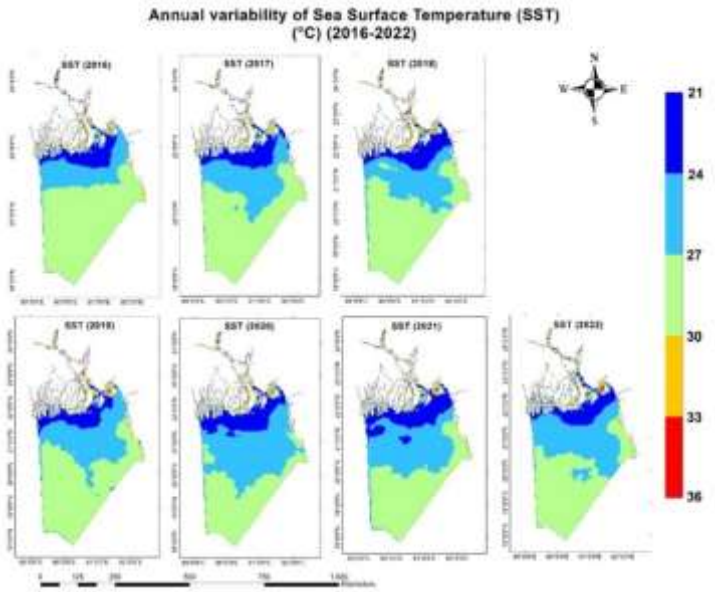

Figure 4: Annual variability of SST (2016-2022)

3.2 Temporal Variability PAR, Kd_490 and SST

3.2.1 Visualization of Annual PAR Variations

PAR values exhibit a distinct seasonal trend, characterized by elevated values during the spring & summer period (around May to July) and reduced values during the winter period (around November to February). This pattern remains constant across all years. From the annual variability graphs (Figure-5), it is observed that the range of PAR values fluctuated between 32.47-54.96 Einstein/m²/day. From the time series graphs of PAR (2016-2022) (Figure-6), each line has a different seasonal pattern, with the maximum values of PAR around 55 Einstein/m²/day, often occurring during the mid-year months. This correlates to the summer season in the Northern Hemisphere, when the sunshine is more direct and the days are longer, leading to more available light for photosynthesis. The lowest values around 32 Einstein/m²/day exist throughout the late and early months of the year, corresponding with the winter season when there is less sunshine due to shorter days and a lower solar angle.

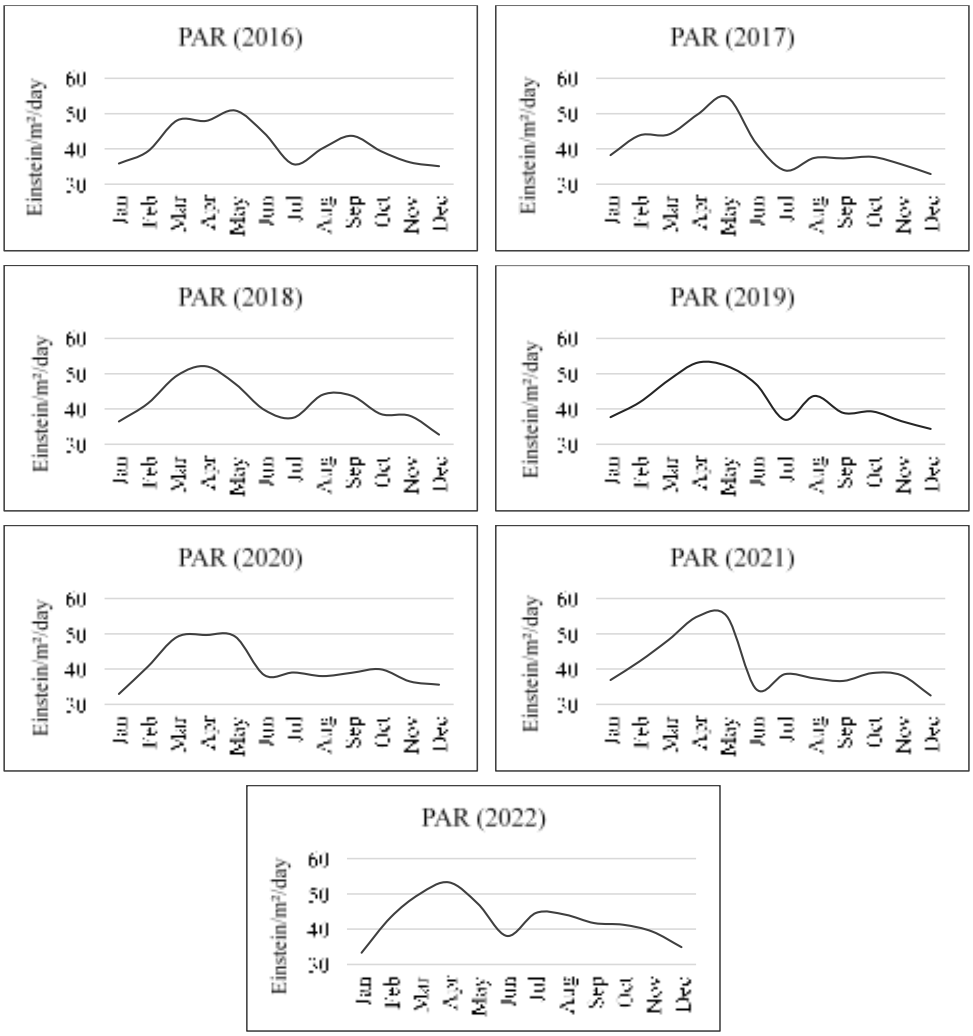

Figure 5: Graphs of annual PAR (2016-2022)

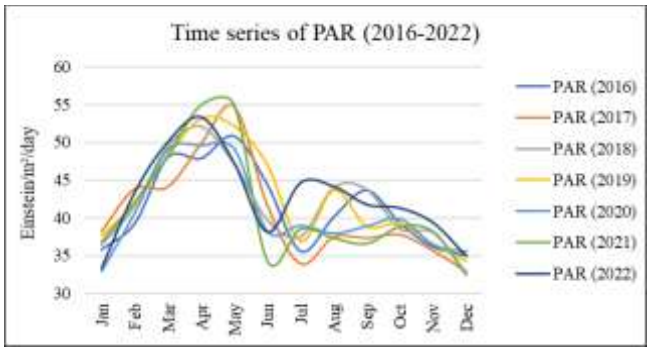

Figure 6: Time series of PAR (2016-2022)

3.2.2 Visualization of Annual Kd Variations:

Graphs of annual Kd variability showed the variation of Kd_490 throughout the year from 2016 to 2022 (Figure-7). There was a seasonal pattern evident in the graphs, with Kd values fluctuating between 0.01- 0.33 m^{-1} throughout the year. The graphs show different patterns each year, suggesting variability in the factors affecting water clarity. For example, higher Kd values indicate more light being absorbed or scattered per meter. These changes are likely related to seasonal climatic factors affecting water transparency, such as monsoons, river runoff, and algal blooms, which are common in marine environments like the EEZ of Bangladesh. Time series graphs of Kd across the years (2016-2022) (Figure-8) showed more fluctuations. A common feature across the years is that the Kd values tend to increase around the middle of the year, particularly in the months of May through August, which suggests a seasonal influence. Towards the end of the year and the beginning of the next year, the Kd values generally decrease, suggesting clearer water conditions.

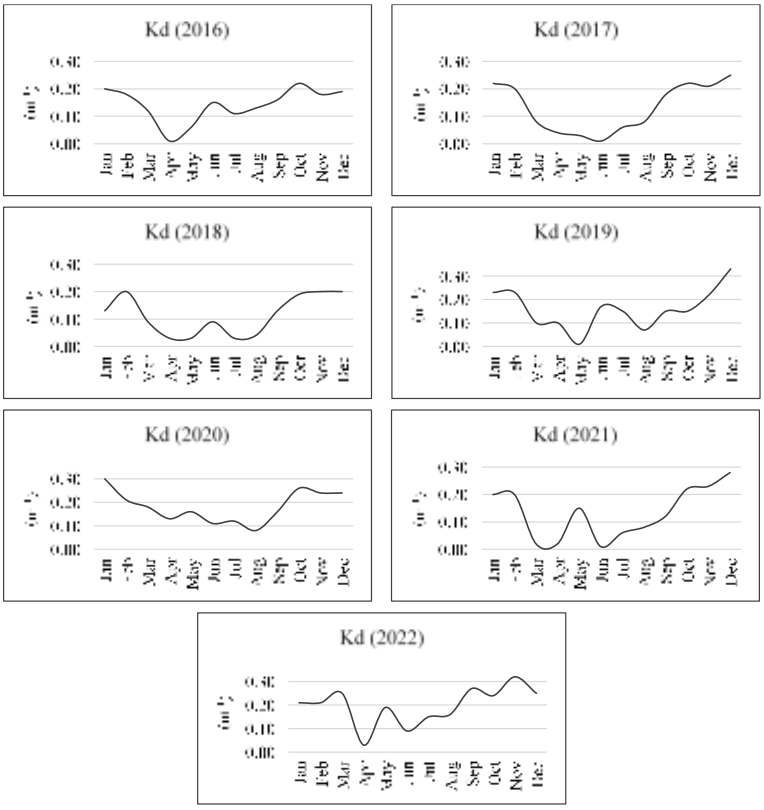

Figure 7: Graphs of annual Kd_490 (2016-2022)

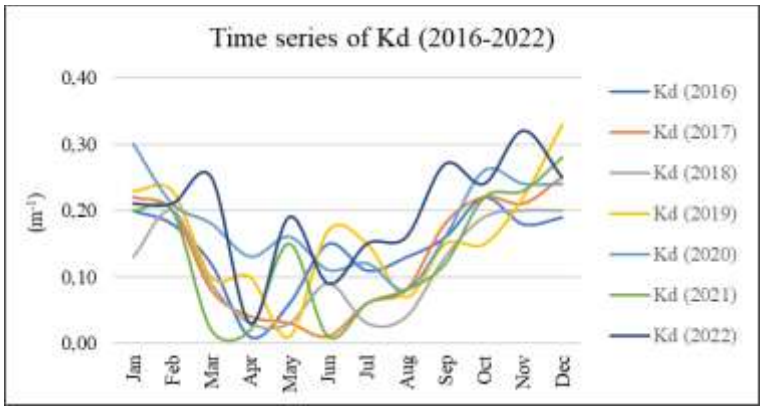

Figure 8: Time series of Kd (2016-2022)

3.2.3 Visualization of Annual SST Variations:

There is a strong seasonal pattern evident in each year's graph, with SST typically peaking in the middle months, suggesting summer circumstances, and reaching its lowest points during the early and later months, suggesting winter conditions. Although the seasonal trend is stable, the peak and trough temperatures fluctuate from year to year (Figure 9). This suggests that each year may encounter slightly varying oceanic and atmospheric conditions impacting SST. While there is some variation in the exact temperatures, fluctuating between 22 °C and 31 °C, observed from the time series graphs of SST between 2016 and 2022 (Figure 10), the overall seasonal pattern is remarkably consistent from year to year. There are subtle differences in the peak temperatures reached in different years and the timing of these peaks.

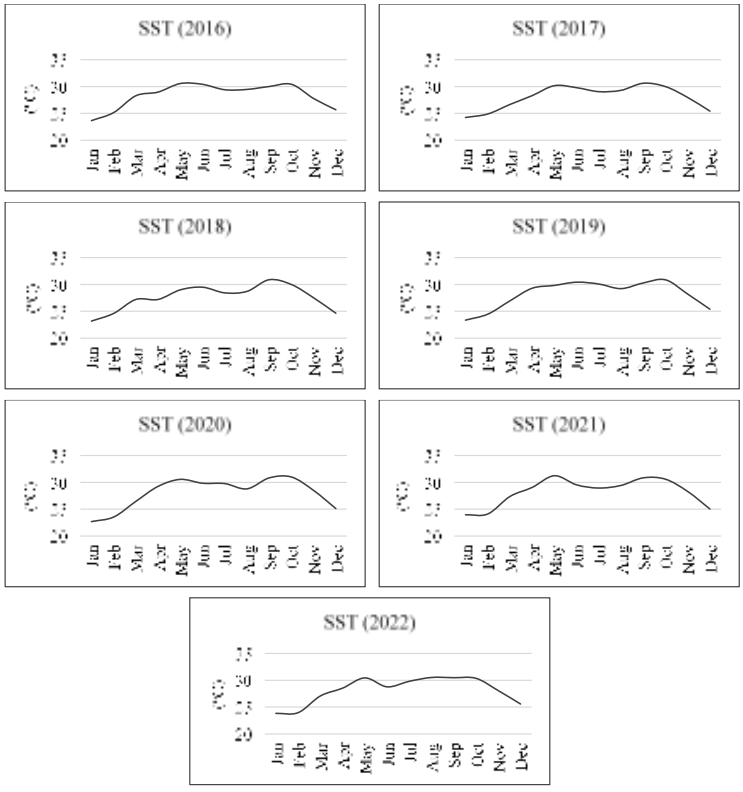

Figure 9: Graphs of annual Kd_490 (2016-2022)

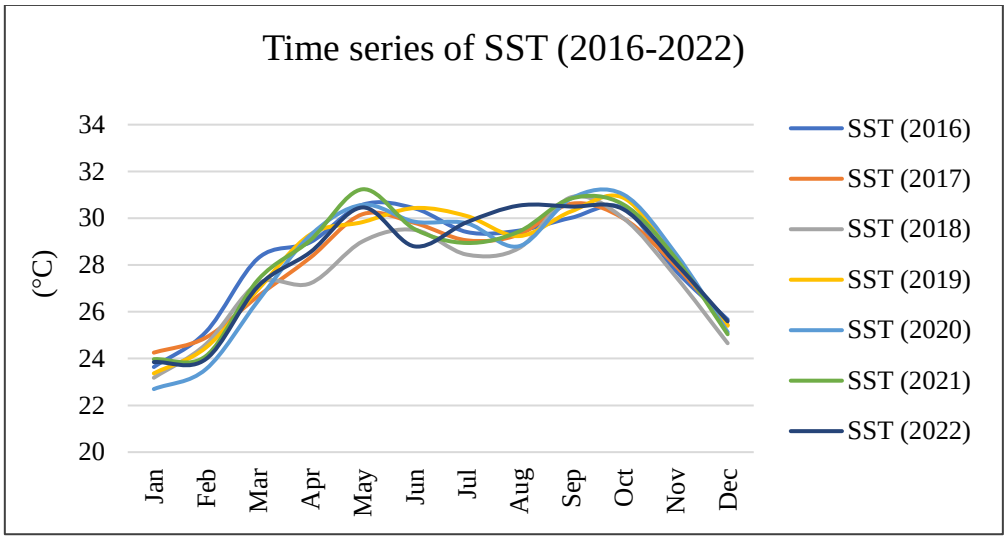

Figure 10: Time series of PAR (2016-2022)

This study presents a comprehensive analysis of the spatial and temporal variability of Photosynthetically Available Radiation (PAR), Diffuse Attenuation Coefficient (Kd_490), and Sea Surface Temperature (SST) in the Bangladesh Exclusive Economic Zone over the period from 2016 to 2022. The findings reveal significant fluctuations in these parameters, which are essential for comprehending the marine biological dynamics in this area.

The observed variability in PAR across the study period, with a high PAR of 55 Einstein/m²/day and low PAR of 32 Einstein/m²/day, suggests a dynamic interplay of atmospheric and oceanographic conditions. (Ocean et al., 2012) observed a high PAR of 47 Einstein/m²/day during 1998 and 2002. Fluctuations in solar radiation have direct implications for primary productivity in the marine ecosystem. Periods of low PAR are indicative of reduced photosynthetic activity, which can impact the base of the food web. This variability might be attributed to monsoonal cycles, cloud cover, and anthropogenic factors like pollution.

In terms of Kd_490, the data shows a trend of increasing water turbidity in certain areas. This increase could be related to land runoff, particularly post-monsoon, and possible anthropogenic activities like overfishing and pollution, leading to changes in phytoplankton composition. The impact of such changes is profound, as it impacts the upper ocean thermodynamics (Mallick et al., 2019)and strongly affects light penetration, influencing both the ecological balance and the heat absorption of the ocean.

The SST data range 22 °C to 31 °C observed from this study indicates a gradual warming trend over the years between 2016-2022, while (Shuva et al., 2022) observed 29.613 °C to 23.446 °C during daytime in the northern Bay of Bengal over the time period of 2000-2019. This subtle rise in SST can have far-reaching consequences, including altering species distributions, impacting weather patterns, and potentially contributing to more frequent and severe tropical storms.

4 Conclusion

The paper presents a combined evaluation of the spatial and temporal dynamics of Photosynthetically Available Radiation (PAR), the Diffuse Attenuation Coefficient at 490 nm (Kd_490), and Sea Surface Temperature (SST) in the Bangladesh Exclusive Economic Zone for 2016-2022. A combination of Aqua MODIS data, SeaDAS processing, and GIS-based

mapping resulted in a unified description of the dynamics of these critical marine environmental parameters in space and time.

The spatial distribution of PAR shows a substantial difference between coastal and offshore waters, driven by differences in water clarity and atmospheric conditions. Minimum PAR was consistently recorded in coastal areas, whereas offshore areas had greater radiation availability, a better indicator of conditions that favor phytoplankton growth. Patterns of Kd_490 indicate that the coastal waters are turbid, which is associated with suspended solids, river outflow, and biological processes, whereas offshore waters are clear. This gradient indicates the interplay of monsoons, on-land inputs, and seasonal mixing in determining the light penetration in the upper ocean.

SST showed a regular seasonal cycle where warm conditions were present in the summer months, and low temperatures were found in winter months, but the long-term pattern showed that there was a gradual warming of the EEZ. This warming may affect stratification, nutrient supply, Monsoon behavior, and the natural operation of marine food webs.

The combined sensitivity of the Bay of Bengal to natural climatic variability and large-scale environmental change is highlighted by the variability observed in PAR, Kd_490, and SST. Knowledge of these dynamics is necessary to track the main productivity, analyze the resilience of the ecosystem, and promote sustainable marine resources management. The results also provide a scientific foundation that can be further developed by incorporating biological, chemical, and hydrodynamic data to enhance future evaluation of marine environmental health in the Bangladesh EEZ.

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GEOSTATISTICAL ALGORITHMS FOR EVALUATING GROUNDWATER QUALITY IN IRRIGATION PRACTICES: A CASE STUDY OF THE GUENFOUDA REGION, NE MOROCCO

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ABSTRACT

Groundwater has become the primary water source utilized in agricultural activities in numerous regions where the climate and drainage systems are inadequate. Consequently, pressure on water resources is exacerbated in Guenfouda, a semi-arid region, primarily due to increased demand and the scarcity of surface water. Poor irrigation water quality will have detrimental effects on soil and agricultural yield, necessitating the determination of water quality to control its suitability for agricultural activities. The objective of this study is to evaluate the suitability of groundwater for irrigation in the Guenfouda region. To achieve this, 30 water points were sampled and subsequently characterized using in situ and laboratory-measured physicochemical parameters. Indices such as Sodium Adsorption Ratio (SAR), Percent Exchangeable Sodium (%Na), Residual Sodium Carbonate (RSC), Kelly Ratio (KR), Permeability Index (PI), and Total Hardness (TH) were calculated. Based on these indices, the majority of samples fall within the acceptable category for irrigation water. The results from the Wilcox and USSL diagrams reveal that most groundwater samples are classified within the good to permissible category, indicating they are safe for irrigation. The application of the Kriging approach, using semi-variogram models, demonstrates that all irrigation indices exhibit significant spatial structure, leading to a reliable prediction model. This article demonstrates that hydrochemical characterization is an important tool for enhancing the understanding of groundwater in the study area. The findings of this study will assist policymakers in effectively managing water resources for rational irrigation use.

Keywords: Groundwater quality; Irrigation indices; Geostatistical modeling; GIS analysis; Guenfouda region; Morocco.

INTRODUCTION

The availability of water in Morocco has been very limited thus far, and it is likely to decrease significantly in the long term due to prolonged periods of drought(Gana and El Amrani 2006; Hssaisoune et al. 2020). Indeed, forecasts have raised concerns, and the kingdom is now one of the countries most threatened by water scarcity by 2040(Abdelmajid et al. 2021; Maddocks, Young, and Reig 2015).

In the Guenfouda region (NE Morocco), the degradation of water resources' quality, particularly groundwater, due to the proliferation of various sources of pollution, poses a threat as serious as quantitative imbalance(El Hafid, Zerrouqi, and Akdim 2017; Ziani, Khattach, and Abderbi 2021). No study on the assessment of irrigation water quality has been undertaken in this region. Therefore, it is crucial to characterize the chemistry of groundwater for its use in agriculture.

The current study aims to determine the suitability of groundwater for irrigation in the studied area. The evaluation of groundwater quality strongly supports previous knowledge about the hydrogeological system of the study area. Furthermore, understanding its suitability is extremely important for effective water management in agriculture and appropriate food production(Malash et al. 2002; Paul et al. 2020).

Geological and hydrogeological contexts

The study area stretches from Zekkara's extreme east to the Moroccan-Algerian border. The Taourirt-Oujda corridor limits it in the north, and the High plateaus limit it in the south. The geological map of the study area (Fig.1) was made using the geological maps of Beni Oukil (1/50000) and Oued el Himer (1/50000). The Triassic, which consists of detrital deposits, doleritic basalts, and occasionally evaporites, rests in angular unconformity on Paleozoic bedrock that has been deformed and structured by several Hercynian tectonic phases(Michard 1976). The Jurassic series constitutes the majority of the region's Mesozoic terrain. They match the red formations of the Lower Triassic-Lias. Their lithology is dominated by dolomite, limestone, marl, and detrital deposits(Oujidi 1994). The Mio-Plio-Quaternary is represented by alluvial deposits and basalt flow. These periods are well exposed in the grabens(Cattaneo 1987).

On a hydrogeological level, the Guenfouda region, which is part of the Isly watershed, closes two hydrogeological units that frequently communicate with one another: the Liasic aquifer, which forms a relatively confined system, and the Plio-Quaternary water table(Mortier, Nguyen Quang, and Sadek 1967; Ziani, Khattach, Nouayti, and Abderbi 2021). These aquifers give rise to several springs, the most notable of which is Ain Guenfouda(Simonot and Thauvin 1971; Ziani, Khattach, Nouayti, Abderbi, et al. 2021). Borehole productivity can exceed 50 L/s in some zones, particularly in fractured areas.

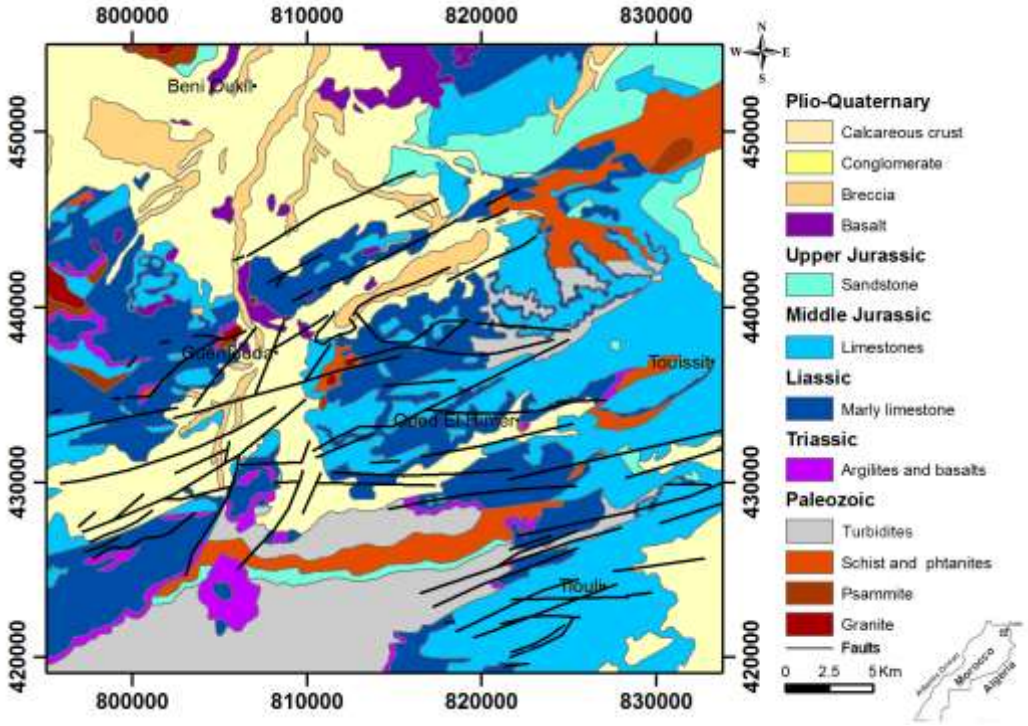

Fig. 1 Geological map with location of the Guenfouda region

MATERIALS AND METHODS

Groundwater samples were collected from 30 wells (Fig. 2) and analyzed by the ONEP (Office National de l'Eau Potable).

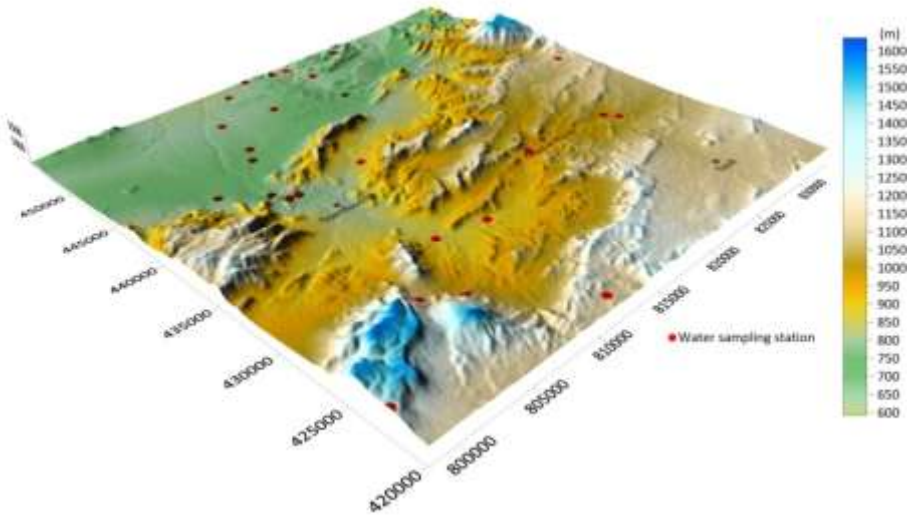

Fig. 2 Showing location of water sampling stations on digital elevation model

Irrigation indices such as Sodium Adsorption Ratio (SAR), Residual Sodium Carbonate (RSC), Sodium Percentage (%Na), Kelly Ratio (KR), Permeability Index (PI), and Total Hardness (TH) were used to determine the suitability of groundwater for irrigation.

SAR is utilized to predict the potential of Na^+ accumulation, initially in the soil through water transport at the expense of Ca^{2+} and Mg^{2+} following the regular use of sodic water. Its equation was formulated by Richards (1968)(Richards 1968). SAR also influences the water percolation

time in the soil. Therefore, it is desirable for the SAR value of irrigation water to be as low as possible.

The %Na is also used to classify water for irrigation purposes. Na^+ forms a chemical bond with the soil by displacing Ca^{2+} and Mg^{2+} ions, reducing water transport capacity(Ayers and Westcot 1985; Singh, Tewari, and Kumar 2020), and such soils become stiff when they dry out(Collins and Jenkins 1996; KG and AS 2020). Indeed, the reaction between Na^+ and CO_3^{2-} produces alkaline soils, while the reaction between Na^+ and chloride produces saline soils. Both types of sodic soils (alkaline/saline) inhibit crop growth(Hitti, MacPherson, and Lefsrud 2023; Todd and Mays 2004). %Na values were calculated by Richards (1968)(Richards 1968).

Kelly (1940)(Kelly 1940) introduced a factor to assess water quality and classification for irrigation based on the concentration of Na^+ compared to Ca^{2+} and Mg^{2+}. KR > 1 indicates an excessive level of Na^+ in the water.

The amount of excess carbonate and bicarbonate compared to alkali earth metal ions influences the suitability of groundwater for irrigation(Bokhari and Khan 1992; Fallatah and Khattab 2023). This excess is called Residual Sodium Carbonate (RSC), which was evaluated using the Eaton (1950)(Eaton 1950) equation.

The PI formula was developed by Doneen (1964)(Doneen 1964) to assess the water movement capacity in the soil as the suitability of any water source for irrigation, as soil permeability is influenced by the long-term use of irrigation water with a high salt concentration.

The United States Salinity Laboratory diagram(U.S.S.L. 1954) concerning the risk of salinity is used for evaluating the suitability of irrigation water quality, while the Wilcox diagram(Wilcox 1955) is a critical graphical method widely used to understand the combination of EC and SAR in evaluating water suitability for irrigation.

Water hardness results from the presence of divalent metal cations and can be calculated as the sum of the concentrations of Ca^{2+} and Mg^{2+} in meq/l equivalent to $CaCO_3$ (Liyanage et al. 2022; Todd and Mays 2004). Among the numerous interpolation methods available in the literature, we adopted the Kriging method because it is the best for standard distribution data(Belkhiri, Tiri, and Mouni 2020; Gharbia et al. 2016). This method involves three steps. Firstly, an exploratory data analysis is executed to explore data and verify their consistency and uniformity, by removing outliers and identifying the statistical distribution. Secondly, spatial correlation or dependence is quantified using semi-variograms.

The application of the Kriging approach with semi-variogram models is related to the expected quadratic difference between paired data values and the distance by which the locations have been separated (Taharin and Roslee 2021). Finally, the developed models are used for prediction. Thus, we reasoned on the best-fitted model for each index. The predictive performances of the fitted models were verified based on spatial cross-validation tests, namely: the mean (M), mean standardized (MS), root mean square (RMS), average standard error (ASE), and root mean square standardized (RMSS).

RESULTS AND DISCUSSION

I. Water quality indices

1. Sodium Adsorption Ratio (SAR)

Based on the SAR range, water samples can be classified into two categories: SAR < 10; (97% of samples) considered excellent, and SAR between 10 and 18; (3% of samples) considered good for irrigation.

2. Residual sodium carbonate (RSC)

RSC values in the study area range from -8.5 to 1.1meq.L-1. All groundwater samples fall within the safety limit for agriculture.

3. Sodium ratio (%Na)

The classification of water samples based on %Na is as follows: excellent (20%), good (47%), permissible (20%), and doubtful (13%). The majority of wells fall into the good category of water for irrigation.

4. Kelly Ratio (KR)

Based on the Kelly index, 83% of water points with KI ≤ 1 are recommended for irrigation, while 17% of water samples with KI ≥ 1 are not suitable for irrigation due to alkali risks(Ramesh and Elango 2012).

5. Permeability Index (PI)

According to Doneen (1964)(Doneen 1964), water samples are classified into two categories: class I (2%, suitable) and class II (98%, good), meaning that the sampled water is suitable for irrigation.

6. Total Hardness (TH)

The classification of water samples based on TH is soft (93%) and moderately hard (7%)(E.P.A. 1986), indicating that the analyzed water is suitable for irrigation.

The study's findings were consistent with those of papers on the hydrogeochemical analysis of groundwater samples from India(Singh, Tewari, and Kumar 2020) and Tunisia(Aouiti et al. 2021), which examined the suitability of groundwater for irrigation using irrigation indices.

II. Graphical interpretation of the USSL diagram and the Wilcox diagram

The % Na plotted against EC values for groundwater samples was depicted in the USSL diagram (Fig. 3), illustrating that, in general, most samples fall within a range from good to permissible, allowing appropriate water use for irrigation purposes.

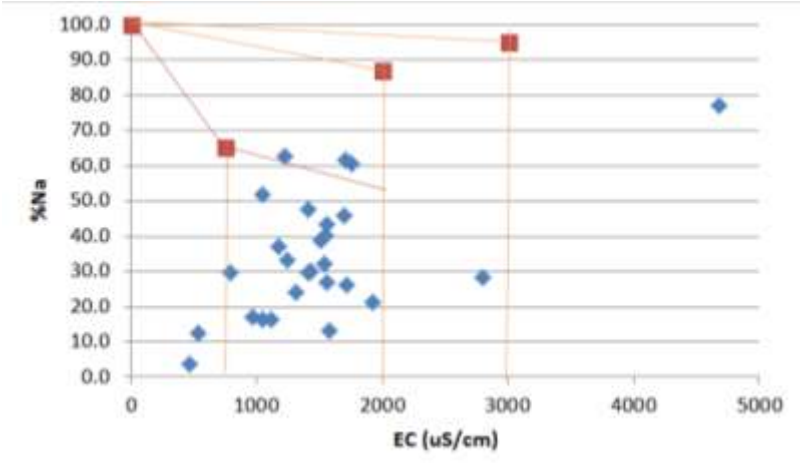

Fig. 3 USSL Diagram indicating the suitability of groundwater

Figure 4 displays groundwater samples falling within the C3S1 field, indicating moderate salinity control with low sodium risk and thus appearing suitable for irrigation use.

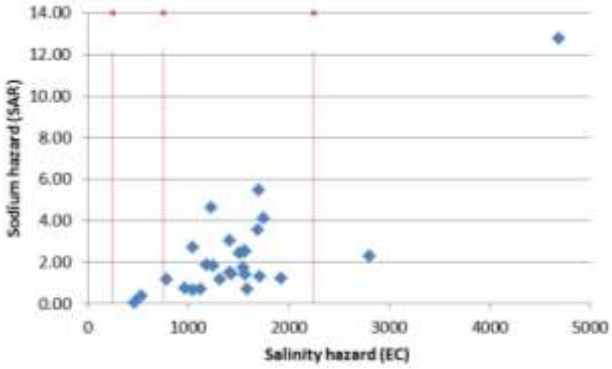

Fig. 4 Wilcox diagram indicating the suitability of groundwater for irrigation

III. Geostatistical modeling of irrigation indices

The predictions are unbiased, with "M" close to zero, indicating that our models are correct or even ideal when it is zero. However, this statistic is dependent on the data scale and insensitive to semivariogram inaccuracies. Therefore, we used "MS" to normalize "M", ideally aiming for it to be zero, confirming the accuracy of the proposed models.

Furthermore, each technique provides variances estimating the prediction variability from known kriging probability values. The RMS is slightly higher than the ASE, indicating that prediction errors were properly evaluated and prediction variability is underestimated. Underestimation of prediction variability is also inferred from the RMSS statistic, which is greater than one, the ideal value for this parameter. The corresponding sill, nugget, and range magnitudes for the best-fitted theoretical models were observed and reported in Table 1. The best-fitted semivariogram models are presented in figures 5 to 9.

Table 1 Characteristics parameters of semivariogram models

Parameter	Model type	Nugget	Sill	Variance	Lag size	Range	M	RMS	ASE	MS	RMSS
SAR	stable	0.1	5.3	2%	1205.0	9639.9	-0.3	2.6	1.4	-0.1	1.6
Na%	Stable	0.0	299.8	0%	2449.1	19592.4	-0.3	18.1	14.9	0.0	1.1
KR	Tetraspherical	0.1	0.5	18%	2424.0	19392.1	0.0	0.8	0.5	0.0	1.3
TH	Exponential	188.6	0.0	-	2411.6	19292.7	-0.1	14.5	14.3	0.0	1.0
PI	Stable	185.2	35.7	519%	3582.3	28658.7	-0.1	15.6	15.3	0.0	1.0

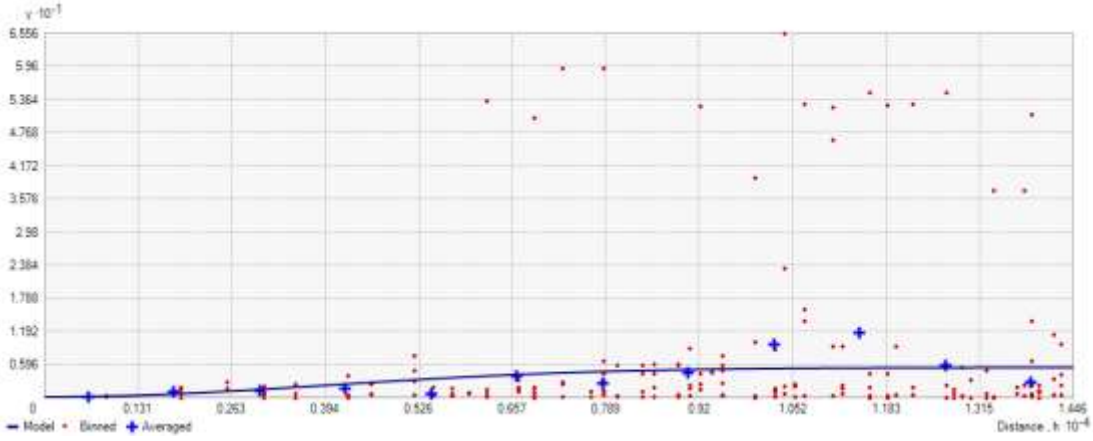

Fig. 5 Best-fitted semivariogram model for SAR indice

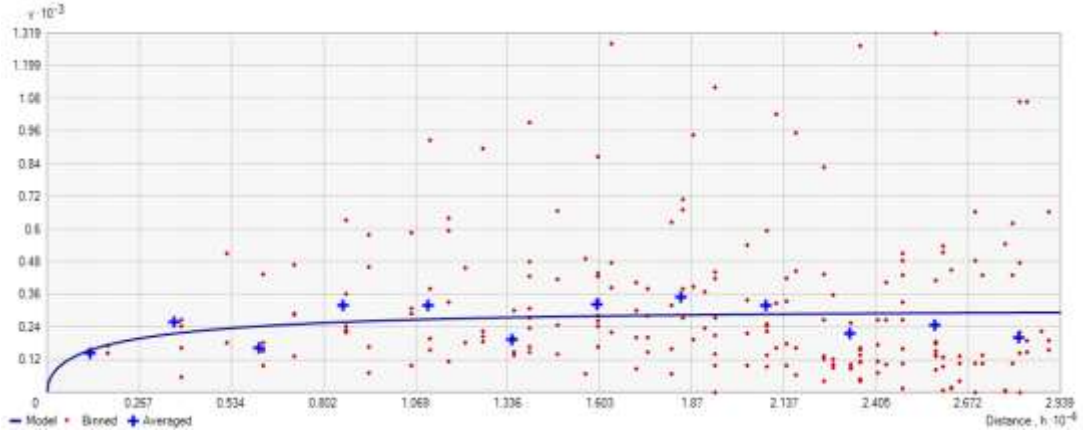

Fig. 6 Best-fitted semivariogram model for NA% indice

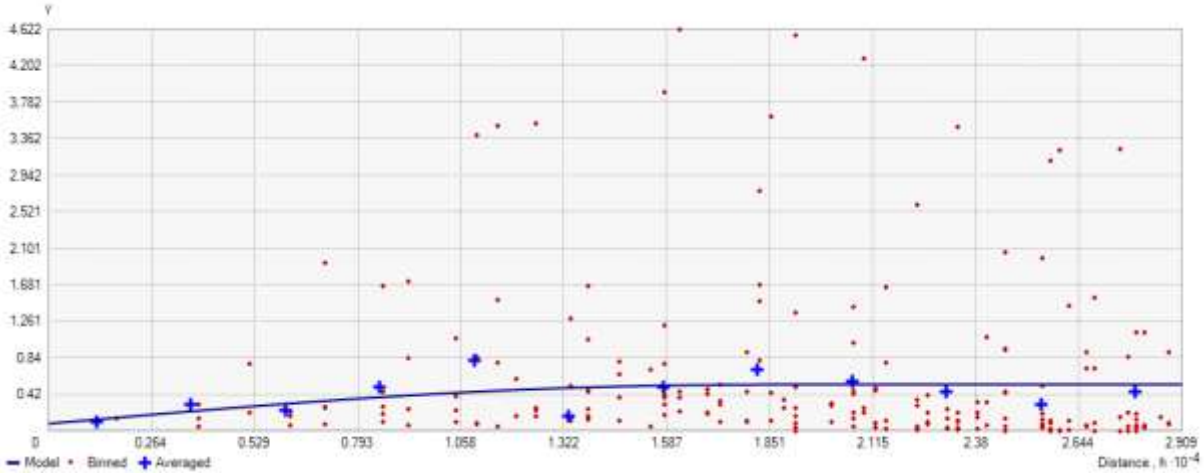

Fig. 7 Best-fitted semivariogram model for KR indice

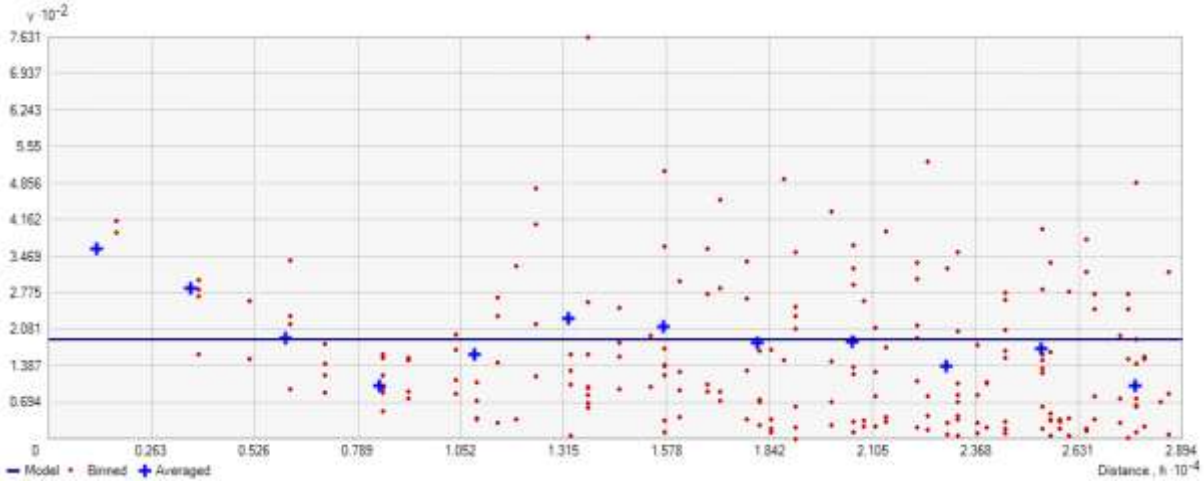

Fig. 8 Best-fitted semivariogram model for TH indice

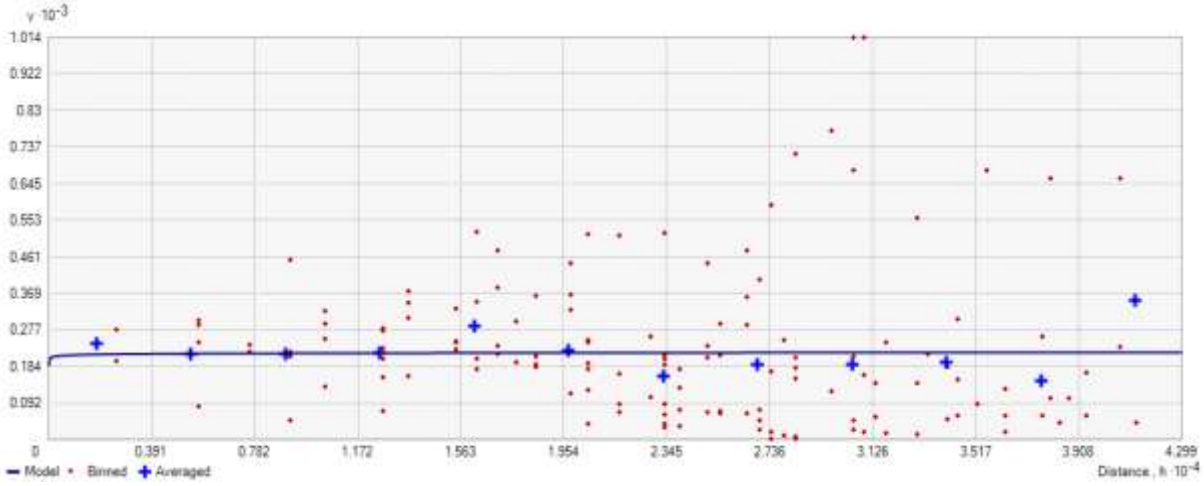

Fig. 9 Best-fitted semivariogram model for PI indice

The ratio of nugget variance to sill, expressed as a percentage, is used as a criterion for classifying the spatial dependence of irrigation factors. This ratio is less than 25% for SAR, %Na, and KR, indicating strong spatial dependence, while for PI, the rate is over 75%, signifying weak spatial support. All irrigation indices exhibit significant spatial structure and thus a good prediction model.

CONCLUSIONS

Agriculture constitutes the main source of income for a large number of people in the Guenfouda region. However, the region faces the adverse effects of excessive agricultural activities due to overexploitation of groundwater and alteration of its quality. This study provides essential information on groundwater quality for irrigation. Overall, all irrigation indices indicate that groundwater in the study area is suitable for agricultural activities. Furthermore, geostatistical analysis confirms that all parameters exhibit significant spatial structure, representing a good prediction model. This article demonstrates that hydrochemical characterization is an important tool for improving the understanding of groundwater quality. The findings of this study will assist policymakers in structuring and developing water resource management.

Statements and Declarations

Funding: The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Competing Interests: The authors have no relevant financial to disclose.

Author Contributions: All authors contributed to this study from conception, reading, and approving the latest version.

Ethical Responsibilities of Authors: All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

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KAZAKİSTAN'IN EKOTURİZM POTANSİYELİNİN ÖNÜNDEKİ ENGELLER VE FIRSATLAR: KATON-KARAGAY MİLLİ PARKI ÖRNEĞİ

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ÖZET

Bu çalışma, Kazakistan'ın en geniş korunan alanı ve UNESCO Dünya Mirası "Altay'ın Altın Dağları" bölgesinin bir parçası olan Katon-Karagay Milli Parkı'nın (KKMP) ekoturizm potansiyelini analiz etmektedir. Araştırmanın amacı, parkın sahip olduğu olağanüstü doğal ve kültürel miras değerleri ile mevcut yönetim, altyapı ve katılım eksiklikleri arasındaki uyumsuzluğu ortaya koymak ve sürdürülebilir bir ekoturizm modeli çerçevesinde çözüm önerileri geliştirmektir. Çalışmada sistematik literatür taraması ve SWOT analizi yöntemleri birlikte kullanılmış, parkın ekolojik bütünlüğü, sosyo-kültürel yapısı, yönetimsel kapasitesi ve turizm planlaması çok boyutlu olarak değerlendirilmiştir. Bulgular, Katon-Karagay'ın zengin biyolojik çeşitliliği, bozulmamış dağ ekosistemleri, endemik tür varlığı, kültürel özgünlük ve güçlü koruma statüsüyle önemli bir ekoturizm potansiyeline sahip olduğunu göstermektedir. Ancak, altyapı yetersizlikleri, kurumsal koordinasyon eksikliği, sınırlı yerel halk katılımı, tanıtım ve pazarlama konularındaki zayıflıklar bu potansiyelin sürdürülebilir biçimde değerlendirilememesine neden olmaktadır. Bu kapsamda çalışma, dört temel bileşenden oluşan bütünleşik bir ekoturizm gelişim modeli önermektedir: etkin yönetişim ve planlama, sürdürülebilir altyapı ve hizmetler, yerel kapasite geliştirme ve paydaş katılımı ile hedef odaklı pazarlama ve markalaşma. Sonuç olarak, Katon-Karagay Milli Parkı'nın uluslararası ölçekte tanınan sürdürülebilir bir ekoturizm destinasyonuna dönüşebilmesi, çevresel koruma ve yerel kalkınmayı dengeleyen uzun vadeli politikaların hayata geçirilmesiyle mümkündür.

Anahtar Kelimeler: Ekoturizm, Katon-Karagay Milli Parkı, Sürdürülebilir Turizm, Korunan Alan Yönetimi, Kazakistan, SWOT Analizi.

BARRIERS AND OPPORTUNITIES FOR ECOTOURISM POTENTIAL IN KAZAKHSTAN: THE CASE OF KATON-KARAGAY NATIONAL PARK

ABSTRACT

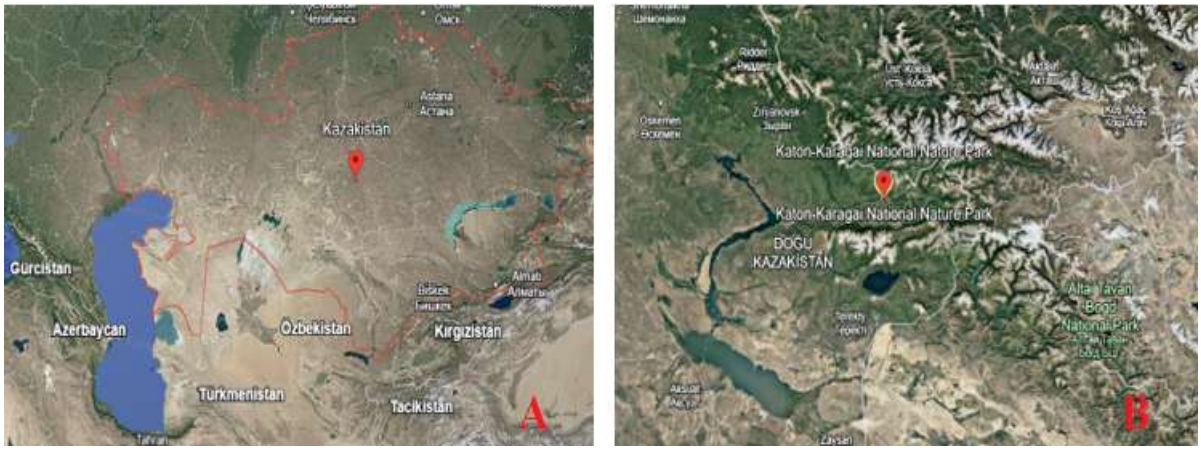
This study analyzes the ecotourism potential of Katon-Karagay National Park (KKNP), the largest protected area in Kazakhstan and part of the UNESCO World Heritage Site "Golden Mountains of Altai." The main objective is to identify the discrepancy between the park's outstanding natural and cultural values and the existing deficiencies in management, infrastructure, and local participation, while proposing solutions within the framework of sustainable ecotourism development. A systematic literature review and SWOT analysis were employed to assess the park's ecological integrity, socio-cultural dynamics, managerial capacity, and tourism planning dimensions. Findings indicate that KKNP possesses remarkable biodiversity, pristine mountain ecosystems, rich endemic flora and fauna, strong legal protection, and authentic cultural heritage, all of which represent significant ecotourism potential. However, weaknesses such as inadequate infrastructure, insufficient institutional coordination, limited community involvement, and weak promotion and marketing strategies hinder the effective realization of this potential. To overcome these challenges, the study proposes an integrated ecotourism development model consisting of four strategic components: effective governance and planning, sustainable infrastructure and visitor services, local capacity building and stakeholder participation, and targeted marketing and branding. In conclusion, transforming Katon-Karagay National Park into a globally recognized sustainable ecotourism destination depends on the implementation of long-term policies that balance environmental protection with local socio-economic development.

Keywords: Ecotourism, Katon-Karagay National Park, Sustainable Tourism, Protected Area Management, Kazakhstan, SWOT Analysis.

1. Giriş

Küresel turizm endüstrisi, iklim değişikliği, biyolojik çeşitlilik kaybı ve kaynakların aşırı tüketimi gibi çevresel sürdürülebilirlik endişelerinin artmasıyla birlikte, geleneksel kitlesel turizm modellerinden sürdürülebilir alternatiflere doğru yapısal bir dönüşüm yaşamaktadır. Bu bağlamda, çevresel korumayı, yerel toplulukların refahını ve ziyaretçi eğitimini temel ilke edinen ekoturizm, turizmin bu üçlü sacayağında denge kuran bir yaklaşım olarak giderek daha fazla önem kazanmaktadır (Fennell, 2020; Honey, 2008). Özellikle COVID-19 sonrası dönemde, doğa ile iç içe, kalabalıktan uzak ve anlamlı seyahat deneyimlerine yönelik artan talep, ekoturizmi sektörün en dinamik bileşenlerinden biri haline getirmiştir.

Orta Asya'nın en büyük ekonomisi ve coğrafyasına sahip olan Kazakistan, bozulmamış doğal alanları, geniş bozkırları, yüksek sıradağları ve zengin kültürel mirası ile önemli bir ekoturizm potansiyeli barındırmaktadır. Ancak, ülke ekonomisinde petrol ve doğalgaz sektörlerinin tarihsel ağırlığı, turizmin özellikle de ekoturizm alanındaki planlama, altyapı yatırımları ve yönetişim modellerinin yetersiz kalmasına neden olmuştur (Government of the Republic of Kazakhstan, 2019; OECD, 2018). Hükümetin son yıllarda ekonomiyi çeşitlendirmeye yönelik girişimleri ve "Yeşil Ekonomi" geçiş planına rağmen, korunan alanlardaki ekoturizm potansiyelinin etkin bir şekilde değerlendirildiğini söylemek güçtür.



Şekil 1. Kazakistan (A) ve Katon-Karagay Milli Parkı (B) uydu görüntüsü (Google Earth, 2025).

Kazakistan'ın (Şekil 1A) bu kullanılmamış potansiyelini simgeleyen en önemli noktalardan biri, ülkenin doğusunda, Rusya ve Çin sınırında yer alan Katon-Karagay Milli (Şekil 1B) Parkı'dır (KKMP). 2001 yılında kurulan ve 643.477 hektarlık alanı ile Kazakistan'ın en büyük milli parkı olan KKMP, aynı zamanda UNESCO'nun "Altay'ın Altın Dağları" (Şekil 2) Dünya Mirası Alanı'nın bir parçasıdır (UNESCO, 2014). Katon-Karagay Milli Parkı, park ve göllerinin (Şekil 3) yanı sıra Avrasya'nın simgesel türlerinden yılkı atları, kar geyiği, kar leoparı (*Panthera uncia*) ve Kara akbaba (Şekil 4 A-B-C-D) gibi nesli tehdit altındaki türlere ev sahipliği yapmaktadır. Aynı zamanda binlerce yıldır süren geleneksel Kazak ve Altay göçebe kültürünü yaşatan bir açık hava müzesi işlevi görmektedir (Kazakistan Cumhuriyeti Çevre, Jeoloji ve Doğal Kaynaklar Bakanlığı, 2021). Bu özellikleri, KKMP'yi yalnızca ulusal değil, küresel ölçekte de eşsiz kılmaktadır.



Şekil 2. Orman örtüsü, Alpin çayırları, kayalık yamaçlar, buzullar ve Belukha Dağı (URl, 1).



Şekil 3.Yazovoye Gölü (Yedi Göl) (URL, 2).

Parkın bu eşsiz özellikleri ve sahip olduğu muazzam potansiyeline karşılık, ciddi altyapı eksiklikleri (ulaşım, konaklama, atık yönetimi), yetersiz yönetim kapasitesi (personel, bütçe), yerel halkın sürece ekonomik ve karar alma düzeyinde dahil olamaması ve zayıf pazarlama stratejileri gibi eksiklikleri vardır. Bu sebeple parkın potansiyeli tam olarak değerlendirilememekte, adeta "saklı bir hazine" olarak kalmaktadır (IUCN, 2017; Turyspekova vd., 2022). Bu durum, turizmden beklenen ekonomik faydanın oluşmamasının yanı sıra, koruma hedefleri ile artan ziyaretçi sayısı arasında oluşabilecek çatışma riskini de beraberinde getirmektedir. Potansiyel ile mevcut durum arasındaki bu belirgin boşluk, bilimsel ve sistematik bir müdahaleyi zorunlu kılmaktadır.



Şekil 4. Yılkı atları (A), Kar geyiği (B) Kar leoparı (C) ve Kara akbaba (D). (URL, 3 ve 4).

Bu çalışma, işte bu boşluğu bilimsel olarak ortaya koymayı ve KKMP'nin sürdürülebilir, katılımcı ve ekonomik olarak canlı bir ekoturizm destinasyonuna dönüşmesi için entegre bir kalkınma modeli önermeyi amaçlamaktadır. Çalışma, mevcut durumu analiz etmenin ötesine geçerek, teori ile pratiği birleştiren ve politika yapıcılar için uygulanabilir bir yol haritası sunmayı hedeflemektedir. Bu kapsamda çalışmanın temel araştırma soruları şunlardır:

1. KKMP'nin mevcut durumu, ekoturizmin çevresel, sosyo-kültürel ve ekonomik sürdürülebilirlik ilkeleri açısından nasıl değerlendirilebilir?

2. Parkın bu potansiyelini sınırlayan içsel (zayıf yönler) ve dışsal (tehditler) faktörler nelerdir ve bu faktörler nasıl bir etkileşim içindedir?

3. Mevcut fırsatları değerlendirip zayıflıkları gidermek suretiyle, sürdürülebilir bir ekoturizm gelişimi için hangi stratejik, bütünleşik model ve politika önerileri geliştirilebilir?



Şekil 5. Geleneksel yurt (A) ve iç kısmı (B). (URL, 5)

2. Yöntem

Bu araştırma, nitel araştırma paradigması içerisinde sistematik literatür taramasına dayanmaktadır. Birincil veri toplama yerine, mevcut bilgi birikimini sentezlemeyi

ve kavramsal bir çerçeve oluşturmayı hedefleyen bu yöntem, erişimi kısıtlı bölgelerdeki konuların incelenmesi için uygundur.

Veri Toplama: Çalışmanın veri kaynaklarını, KKMP ve Kazakistan'da ekoturizm ile ilgili akademik makaleler, kitaplar, Kazakistan hükümeti ve uluslararası kuruluşlara (UNWTO, UNDP, IUCN) ait resmi raporlar ve istatistikler oluşturmuştur. Web of Science, Scopus ve Google Scholar gibi veri tabanlarında ilgili anahtar kelimelerle taramalar yapılmıştır.

Veri Analizi: Toplanan verilerin analizinde içerik analizi ve betimsel analiz yöntemleri kullanılmıştır. İçerik analizi ile metinler, önceden belirlenen temalar (yönetim, altyapı, yerel katılım vb.) çerçevesinde kodlanmış ve kategorilere ayrılmıştır. Betimsel analizle ise istatistiksel veriler özetlenmiş ve yorumlanmıştır. Analiz sürecinin merkezinde, parkın içsel ve dışsal faktörlerini organize bir şekilde değerlendirmeyi sağlayan SWOT analizi (Güçlü yönler, Zayıf yönler, Fırsatlar, Tehditler) bulunmaktadır.

3. Bulgular

3.1. Katon-Karagay Milli Parkı'nın Mevcut Durum Analizi

KKMP, ekoturizm ilkeleri açısından değerlendirildiğinde, potansiyel ile gerçeklik arasında belirgin ve endişe verici bir fark olduğu görülmektedir. Bu fark, sürdürülebilirliğin üç temel boyutunda da açıkça gözlemlenmektedir.

- **Çevresel Sürdürülebilirlik:** Park, UNESCO Dünya Mirası statüsü ve ulusal koruma yasalarıyla desteklenen güçlü bir yasal çerçeveye ve 900'ü aşkın vasküler bitki türü, 300'den fazla omurgalı türü (kar leoparı, boz ayı, Altay argali) ile olağanüstü bir biyolojik çeşitliliğe sahiptir. Bu, çevresel sürdürülebilirliğin temelini oluşturmaktadır. Ancak, bu potansiyel ciddi riskler altındadır. Etkin bir ziyaretçi yönetim sistemi ve bilimsel olarak belirlenmiş bir taşıma kapasitesi uygulamasının olmaması, hassas habitatlarda aşınmaya ve rahatsızlığa neden olmaktadır. Ayrıca, atık yönetimi sistemlerinin (özellikle plastik atıklar) yok denecek düzeyde olması, su kaynakları kirliliği ve görüntü kirliliği riskini beraberinde getirmektedir. İklim değişikliğinin etkisiyle eriyen buzullar ise uzun vadeli bir başka tehdit olarak kayıtlara geçmektedir.

- **Sosyo-Kültürel Sürdürülebilirlik:** Parkın en büyük avantajlarından biri, binlerce yıldır süren otantik Kazak ve Altay göçebe kültürünün parkta canlı bir şekilde yaşatılıyor olmasıdır. Geleneksel çadır konaklamaları (yurt), atlı göçer yaşam, şamanistik gelenekler ve el sanatları, ziyaretçiler için benzersiz bir kültürel deneyimi potansiyelini barındırmaktadır. Fakat, yerel halkın turizm gelirlerinden adil bir pay alamaması, turizmle ilişkili karar alma süreçlerine (örneğin, yönetim planlaması) dahil edilmemesi ve kültürel değerlerin ticarileşerek özünü kaybetme (örneğin, otantik olmayan gösteriler) riski, sosyo-kültürel sürdürülebilirliği ciddi şekilde zayıflatmaktadır. Yerel topluluklar ile park yönetimi arasında güven ve etkili iletişim eksikliği bulunmaktadır.

- **Ekonomik Sürdürülebilirlik:** Turizmden elde edilen gelir hem park yönetimi (yetersiz bütçe, ekipman eksikliği) hem de yerel halk (bölgede yüksek seyreden işsizlik oranları) için yetersiz kalmaktadır. Mevcut turizm ekonomisinin yapısı incelendiğinde, gelirin büyük kısmının bölge dışındaki tur operatörleri ve yatırımcılara aktığı görülmektedir. Konaklama ve yeme-içme tesisleri son derece sınırlı olup, çoğunlukla temel ihtiyaçları karşılamaktan uzak, düşük kapasiteli ve düşük gelir modeline sahiptir. Bu durum, ziyaretçi memnuniyetini, ortalama kalış süresini ve kişi başı harcamayı düşürmekte, dolayısıyla turizmin ekonomik katma değerini sınırlandırmaktadır.

3.2. SWOT Analizi

KKMP'nin mevcut durumunu stratejik bir perspektifle özetleyen ve geleceğe yönelik çıkarımlar yapmayı mümkün kılan SWOT analizi aşağıdaki tabloda detaylandırılmıştır (Tablo 1). Bu analiz, içsel ve dışsal faktörlerin kesişiminden doğan fırsatlar ve tehditleri net bir şekilde ortaya koymaktadır.

Tablo 1: Katon-Karagay Milli Parkı SWOT Analizi

	GÜÇLÜ YÖNLER (Strengths)	**ZAYIF YÖNLER (Weaknesses)**
İÇSEL FAKTÖRLER	S1. UNESCO Dünya Mirası statüsü ve güçlü koruma statüleri.	W1. Ulaşım, konaklama ve temel altyapının yetersiz ve kalitesiz olması.
	S2. Olağanüstü doğal güzellikler ve biyolojik çeşitlilik (kar leoparı, Belukha Dağı).	W2. Profesyonel turizm hizmeti (rehberlik, iletişim) ve insan kaynağı eksikliği.
	S3. Otantik ve canlı bir göçebe kültürel mirasın varlığı.	W3. Yetersiz bütçe, personel ve etkin bir yönetim planı eksikliği.
	S4. Geniş ve el değmemiş bir araziye sahip olması.	W4. Ziyaretçi yönetimi ve taşıma kapasitesi sistemlerinin olmaması.
		W5. Markalaşma, tanıtım ve pazarlama eksikliği.
	FIRSATLAR (Opportunities)	**TEHDİTLER (Threats)**
DIŞSAL FAKTÖRLER	O1. Artan küresel ilgi (ekoturizm, macera turizmi, yavaş seyahat).	T1. Plansız ve kontrolsüz turizm nedeniyle doğal ve kültürel kaynakların bozulma riski.
	O2. Kazakistan'ın turizmi çeşitlendirme ve ekonomiyi canlandırma stratejisi.	T2. İklim değişikliğinin ekosistemler ve buzullar üzerindeki olumsuz etkileri.
	O3. UNDP, IUCN gibi uluslararası kuruluşlardan teknik ve finansal destek potansiyeli.	T3. Yerel halk ile park yönetimi/ziyaretçiler arasında çıkar çatışmaları yaşanması.
	O4. "İpek Yolu" rotasının bir parçası olma potansiyeli.	T4. Yasa dışı avcılık, odun kesimi ve kaçak yapılaşma tehdidi.
	O5. Yerel halk için alternatif gelir kaynakları yaratma fırsatı.	T5. Bölgedeki diğer destinasyonlarla (Altay Cumhuriyeti) artan rekabet.

4. Tartışma: Entegre Bir Ekoturizm Gelişim Modeli Önerisi

SWOT analizinden elde edilen bulgular, KKMP'deki sorunların birbiriyle derinden bağlantılı ve sistemik olduğunu, dolayısıyla parçalı müdahalelerle çözülemeyeceğini açıkça göstermektedir. Zayıf bir altyapı (W1), etkisiz pazarlama (W5) ile birleştiğinde, olağanüstü doğal güzellikler (S2) ve kültürel mirasın (S3) varlığı bir anlam ifade etmemekte; aksine, kontrolsüz artan ziyaretçi sayısı (T1) bu değerleri tehdit eder hale gelmektedir. Bu nedenle, sorunları bir bütün olarak ele alan, sürdürülebilirliğin üç boyutunu da merkezine yerleştiren ve dört temel bileşenden oluşan entegre bir ekoturizm gelişim modeli önerilmektedir.

A. Yönetişim ve Planlama: Mevcut yönetim planının, tüm paydaşların (yerel halk, STK'lar, özel sektör) katılımıyla revize edilerek etkin ve şeffaf bir şekilde uygulanması esastır. Bu kapsamda:

- **Akıllı Ziyaretçi Yönetimi:** Parka girişler için çevrimiçi ön rezervasyon sistemi getirilmeli, farklı zonlar ve aktiviteler için taşıma kapasiteleri bilimsel olarak belirlenmeli ve

bu kapasitelere sıkı şekilde uyulmalıdır. Dinamik fiyatlandırma gibi araçlarla ziyaretçi akışı yönetilebilir.

- **Fonksiyonel ve Katılımcı Zonlama:** Park, "yoğun kullanım" (ziyaretçi merkezleri, temel tesisler), "hafif kullanım" (belirlenmiş doğa yürüyüşü parkurları), "vahşi yaşam koruma" (rehber eşliğinde, sınırlı giriş) ve "kültürel miras" zonlarına ayrılarak aktiviteler ve altyapı buna göre düzenlenmelidir.
- **Şeffaf ve Sürdürülebilir Koruma Fonu:** Giriş ücretleri, konaklama vergileri, bağışlar ve cezaların bir kısmı, parkın korunması, araştırma projeleri, izleme çalışmaları ve yerel kalkınma projeleri için ayrılan, şeffaf yönetilen özel bir fona aktarılmalıdır.

B. Altyapı ve Hizmet Geliştirme:

- **Sürdürülebilir Eko-Kulübeler ve Doğa Dostu Kamp Alanları:** Yerel mimariye uygun, yenilenebilir enerji (güneş panelleri, mikro hidroelektrik) kullanan, su tasarruflu arıtma sistemleri, kompost tuvalet ve etkin atık yönetimi olan, düşük kapasiteli ama yüksek konforlu konaklama tesisleri teşvik edilmelidir. İnşaatlarda yerel malzemeler kullanılmalıdır.
- **Yumuşak ve Sürdürülebilir Ulaşım:** Park içinde özel araç trafiği sınırlandırılarak, belirli noktalara elektrikli/minibüs servisleri veya geleneksel ulaşım yöntemleri (at, katır) kullanılmalıdır. Park girişlerine ve ana merkezlere bisiklet kiralama istasyonları kurulabilir.
- **Etkileşimli Ziyaretçi Merkezleri ve Açık Hava Müzeleri:** Parkın doğal ve kültürel değerleri, koruma önemi ve kuralları hakkında eğitim veren, dijital ekranlar, etkileşimli sergiler ve canlı demonstrasyonlar (el sanatları atölyeleri) içeren modern ziyaretçi merkezleri park girişlerine kurulmalıdır.

C. Yerel Katılım ve Ekonomik Fayda:

- **Ekoturizm Kooperatifleri ve Mikro-Kredi/Mentorluk Desteği:** Yerel halkın konaklama (ev pansiyonculuğu), rehberlik, atlı safari, geleneksel yemek, el sanatları satışı gibi hizmetleri sunabildiği, geliri adil bir şekilde paylaştığı kooperatifler kurulmalı ve bu girişimler mikro-krediler ve iş geliştirme mentorluğu ile desteklenmelidir.
- **Zorunlu Yerel Rehberlik ve Kapsamlı Kapasite Eğitimleri:** Hassas doğa ve kültür rotalarına girişlerde, eğitimden geçirilmiş ve sertifikalandırılmış yerel rehber kullanımı zorunlu hale getirilmelidir. Yerel halka turizm, girişimcilik, yabancı dil (İngilizce, Çince), ilk yardım, müşteri hizmetleri ve dijital okuryazarlık eğitimleri verilmelidir.
- **Yerel Tedarik Zinciri ve İstihdam Taahhüdü:** Parktaki tüm işletmelerin (otel, restoran, tur şirketleri) mümkün olduğunca yerel üreticilerden (çiftçiler, balıkçılar, el sanatçıları) tedarik yapması teşvik edilmeli ve park yönetimi ile büyük yatırımcılar, personel alımlarında yerel halka öncelik verme taahhüdünde bulunmalıdır.

D. Hedefli Pazarlama ve Markalaşma:

- **Niş ve Dijital Öncelikli Pazarlama:** Kitlesel turizm yerine, dağcılar, doğa fotoğrafçıları, kuş gözlemcileri, kültür araştırmacıları, macera arayan yüksek gelirli gezginler ve ailelere yönelik özelleştirilmiş pazarlama stratejileri geliştirilmelidir. Sosyal medya, seyahat blogları, influencer işbirlikleri ve SEO çalışmaları etkin kullanılmalıdır.
- **Dijital Hikaye Anlatımı ve Görsel İçerik Stratejisi:** Parkın UNESCO statüsü, "kar leoparının izinde" safari, göçebe kültürüyle iç içe yaşam, Belukha Dağı tırmanışı gibi benzersiz hikayeleri profesyonelce (yüksek kaliteli fotoğraf, drone çekimleri, belgesel tadında kısa

videolarla) anlatılmalı, uluslararası seyahat dergileri ve belgesel kanallarıyla işbirliği yapılmalıdır.

- **Sertifikasyon, Kalite Güvence ve İşbirlikleri:** Park ve parktaki işletmeler için uluslararası geçerli sürdürülebilir turizm sertifikaları (örneğin, GSTC kriterleri) alınması teşvik edilerek, ziyaretçilere kalite ve sürdürülebilirlik garantisi verilmeli, böylece pazarda farklılaşma sağlanmalıdır.

Bu modelin başarısı, yerel toplulukların, sivil toplum kuruluşlarının, özel sektörün ve ulusal düzeydeki karar vericilerin güçlü işbirliği, koordinasyon ve siyasi irade ile doğrudan ilişkilidir. Ulusal düzeyde bir "Korunan Alanlarda Ekoturizm Eylem Planı"nın hazırlanması ve uygulanması, yerel düzeyde ise sürekli kapasite geliştirme, izleme ve değerlendirme mekanizmalarının kurulması kritik öneme sahiptir.

5. Sonuç ve Öneriler

Bu çalışma, Katon-Karagay Milli Parkı'nın (KKMP) küresel standartlarda bir "ekoturizm destinasyonu" olma potansiyeli ile "altyapıdan yoksun, zayıf yönetişimli bir doğa turizmi noktası" olan mevcut durumu arasında kritik bir uçurum olduğunu ortaya koymuştur. Yapılan analizler, parkın UNESCO Dünya Mirası statüsü, olağanüstü biyolojik çeşitliliği ve canlı kültürel mirası gibi güçlü yönlerinin, yetersiz altyapı, sınırlı yerel katılım ve etkisiz pazarlama gibi zayıflıklar nedeniyle gölgelendiğini açıkça göstermektedir. Benzer şekilde, küresel ekoturizm talebi ve hükümetin turizmi çeşitlendirme çabaları gibi fırsatlar, kontrolsüz turizm baskısı ve iklim değişikliği gibi tehditlerle karşı karşıyadır. Bu nedenle, parkın sahip olduğu muazzam potansiyelin gerçek anlamda değerlendirilebilmesi, ancak zayıf yönlerin ve tehditlerin sistematik, koordineli ve kararlı bir şekilde ele alınmasıyla mümkün olabilecektir.

Önerilen dört ayaklı (Yönetişim ve Planlama, Altyapı ve Hizmet Geliştirme, Yerel Katılım ve Ekonomik Fayda, Hedefli Pazarlama ve Markalaşma) entegre ekoturizm modeli, bu zorlu dönüşüm için kapsamlı bir yol haritası ve stratejik bir çerçeve niteliğindedir. Bu modelin başarıyla uygulanması halinde, aşağıdaki somut çıktıların elde edilmesi beklenmektedir:

1. **Artırılmış Koruma Etkinliği:** Bilimsel zonlama ve akıllı ziyaretçi yönetimi sayesinde parkın ekolojik bütünlüğü ve biyolojik çeşitliliği korunacak, koruma-kullanma dengesi sağlanacaktır.

2. **Güçlendirilmiş Yerel Kalkınma:** Yerel kooperatifler, zorunlu rehberlik ve yerel tedarik zinciri ile turizm gelirleri yerelde kalacak, istihdam artacak ve sosyo-ekonomik refah yükselecektir. Bu, aynı zamanda yerel halkın parkı bir tehdit değil, bir değer olarak görmesini teşvik edecek ve koruma çabalarına desteklerini artıracaktır.

3. **Yüksek Kaliteli Ziyaretçi Deneyimi:** Sürdürülebilir altyapı, eğitimli rehberler ve hedefe yönelik pazarlama ile ziyaretçilere unutulmaz, nitelikli, eğitici ve sorumlu bir seyahat deneyimi sunulacak, böylece destinasyonun itibarı ve tekrar ziyaret oranları artacaktır.

Politika ve Uygulama Önerileri:

Bu modelin hayata geçirilebilmesi için aşağıdaki adımların atılması kritik öneme sahiptir:

- **Acil Eylem:** Kazakistan Çevre Bakanlığı öncülüğünde, KKMP için "2025-2030 Ekoturizm Master Planı" acilen hazırlanmalı ve bu plan, önerilen modeli temel almalıdır.

- **Mevzuat Düzenlemesi:** Yerel halkın turizm gelirlerinden adil pay almasını ve karar süreçlerine katılımını güvence altına alan, ayrıca sürdürülebilir altyapı standartlarını zorunlu kılan yasal düzenlemeler yapılmalıdır.

- **Kamu-Özel-Sektör İşbirliği (KÖS):** Altyapı yatırımları ve hizmet geliştirme için KÖS modelleri teşvik edilmeli, özel sektör yatırımları sürdürülebilirlik kriterlerine bağlanmalıdır.

- **Kapasite Geliştirme Programı:** Yerel halk ve park personeli için sürekli ve kapsamlı bir eğitim programı (dil, girişimcilik, rehberlik, dijital pazarlama) ulusal ve uluslararası fonlarla desteklenmelidir.

Bu çalışmanın, Kazakistan'daki karar vericiler, park yöneticileri, yerel yönetimler, sivil toplum kuruluşları ve yerel paydaşlar için somut bir eylem rehberi ve tartışma belgesi olması umulmaktadır. Katon-Karagay Milli Parkı'nın, Orta Asya'nın önde gelen, sürdürülebilirliği ile rol model bir ekoturizm merkezine dönüşmesi, ancak bu tür bütünleşik yaklaşımların benimsenmesi ve kararlılıkla uygulanmasıyla mümkün olacaktır.

Gelecek Çalışmalar için Öneriler: Bu çalışma, teorik bir model sunmakla birlikte, pratikteki geçerliliğini test etmek amacıyla gelecek araştırmalara ihtiyaç duymaktadır:

1. **Birincil Saha Araştırması:** Önerilen modelin bileşenlerine yönelik yerel halk, ziyaretçiler, tur operatörleri ve park yöneticileriyle derinlemesine mülakatlar ve anketler yapılarak modelin uygulanabilirliği, öncelikleri ve potansiyel engelleri detaylıca incelenmelidir.

2. **Karşılaştırmalı Analiz:** Model, benzer özelliklere sahip diğer korunan alanlarda (örneğin, Nepal'deki Sagarmatha Milli Parkı veya Tanzanya'daki Serengeti) uygulanan başarılı modellerle karşılaştırmalı olarak analiz edilerek zenginleştirilebilir.

3. **Ekonomik Fizibilite Çalışması:** Önerilen altyapı yatırımları ve işletme modellerinin ekonomik fizibilitesi ayrıntılı bir şekilde hesaplanmalıdır.

4. **İklim Değişikliği Etki Analizi:** İklim değişikliğinin parkın ekosistemleri ve turizm potansiyeli üzerindeki spesifik etkileri modellenerek, modele uyum stratejileri entegre edilmelidir.

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HAVA YOLU ŞİRKETLERİNDE SÜRDÜRÜLEBİLİRLİK PERFORMANSININ MEREC TABANLI MABAC VE MARCOS YAKLAŞIMI İLE DEĞERLENDİRİLMESİ

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ÖZET

Havacılık sektörü, küresel CO_2 emisyonlarının yaklaşık %2–3'ünü oluşturmaktadır. Ancak, sektörün iklim değişikliği üzerindeki toplam etkisinin sadece bu doğrudan emisyonlardan değil, aynı zamanda diğer atmosferik etkilerden dolayı yaklaşık iki kat daha fazla olduğu belirtilmektedir. Bu yönüyle havacılık, karayolu taşımacılığının ardından ulaşım sektöründe iklim değişikliğine en fazla katkıda bulunan ikinci alan olarak değerlendirilir. Bu çerçevede havacılık sektörü, artan çevresel baskılar ve sürdürülebilir kalkınma hedefleri doğrultusunda çevresel, sosyal ve yönetişim (ÇSY) performansını iyileştirmeye yönelik stratejiler geliştirmektedir. Hava yolu şirketleri için sürdürülebilirlik, çevresel etkilerin azaltılmasını ifade etmenin yanı sıra sosyal sorumluluk, kurumsal yönetim ve operasyonel verimlilik alanlarında dengeli bir gelişimi de gerektirmektedir. Bu kapsamda, sektördeki sürdürülebilirlik performansının bütüncül ve analitik biçimde değerlendirilmesi, stratejik karar alma süreçleri açısından kritik bir önem taşımaktadır. Bu çalışmada, 5 uluslararası hava yolu şirketinin (Türk Hava Yolları, Lufthansa Hava Yolları, Copa Hava Yolları, Singapore Hava Yolları ve Qatar Hava Yolları) 2020–2023 yılları arasındaki sürdürülebilirlik performansları çok kriterli karar verme (ÇKKV) yaklaşımlarıyla analiz edilmiştir. Analiz kapsamında çevresel, sosyal ve yönetişim olmak üzere üç ana kriter altında 9 alt kriter değerlendirmeye alınmıştır. Kriter ağırlıkları, öznel yargılardan ziyade nesnel verilere dayanan MEREC yöntemiyle belirlenmiş; elde edilen ağırlıklar MABAC ve MARCOS yöntemlerine entegre edilerek yıllara göre şirket sıralamaları belirlenmiştir. Lufthansa Hava Yolları 2020–2023 yılları içerisinde hem MABAC hem de MARCOS yöntemleri açısından en yüksek sürdürülebilirlik performansını gösteren hava yolu şirketi olmuştur. Ayrıca, yıllar arasındaki sıralama farklılıkları, hava yolu şirketlerinin sürdürülebilirlik stratejilerinde dönemsel değişikliklerin etkili olduğunu göstermektedir. Çalışma, havacılık sektöründe ÇSY performansını bütüncül bir yaklaşımla değerlendiren entegre bir ÇKKV modeli sunmaktadır. Ayrıca, farklı ağırlıklandırma yöntemlerinin duyarlılık etkisini ortaya koyarak karar vericilere daha sağlam bir analitik temel sağlamaktadır.

Anahtar Kelimeler: Sürdürülebilirlik, Havacılık sektörü, ÇSY, Çok kriterli karar verme (ÇKKV), Duyarlılık analizi.

EVALUATION OF SUSTAINABILITY PERFORMANCE IN AIRLINA COMPANIES USING MEREC-BASED MABAC AND MARCOS APPROACHES

ABSTRACT

The aviation sector accounts for approximately 2–3% of global CO_2 emissions. However, it is reported that the sector's total impact on climate change is approximately twice as high, due not only to these direct emissions but also to other atmospheric impacts. In this respect, aviation is considered the second-largest contributor to climate change in the transportation sector, after road transport. In this context, the aviation sector is developing strategies to improve its environmental, social, and governance (ESG) performance in line with increasing environmental pressures and sustainable development goals. For airline companies, sustainability not only implies reducing environmental impacts but also requires balanced development in social responsibility, corporate governance, and operational efficiency. In this context, a holistic and analytical assessment of the sector's sustainability performance is critical for strategic decision-making processes. In this study, the sustainability performance of five international airlines (Turkish Airlines, Lufthansa Airlines, Copa Airlines, Singapore Airlines, and Qatar Airways) between 2020 and 2023 was analyzed using multi-criteria decision-making (MCDM) approaches. Within the scope of the analysis, nine sub-criteria were evaluated under three main criteria: environmental, social, and governance. Criteria weights were determined using the MEREC method, which relies on objective data rather than subjective judgments. The resulting weights were integrated with the MABAC and MARCOS methods to determine company rankings by year. Lufthansa Airlines achieved the highest sustainability performance between 2020 and 2023, based on both the MABAC and MARCOS methods. Furthermore, the differences in rankings between years indicate that seasonal changes are influential in airlines' sustainability strategies. The study presents an integrated MCDM model that evaluates ESG performance in the aviation sector with a holistic approach. It also provides decision-makers with a more robust analytical basis by demonstrating the sensitivity impact of different weighting methods.

Keywords: Sustainability, Aviation sector, ESG, Multi-Criteria Decision Making (MCDM), Sensitivity analysis.

1. GİRİŞ

Sürdürülebilirlik, var olan bir şeyin ya da bir durumun sürdürülmesi, daimi olma yeteneği olarak adlandırılan ve farklı alanlardaki ilişkileri birbiri ile uyumlu kılmak zorunluluğuna işaret eden bir kavramdır. İngilizce karşılığı "sustainability" olan sürdürülebilirlik kavramı (Şen vd., 2018) literatürde genellikle bugünün ihtiyaçlarını, gelecek nesillerin kendi ihtiyaçlarını karşılama kapasitesini tehlikeye atmadan karşılamak olarak tanımlanmaktadır (WCED, 1987).

Havacılık sektörü, küresel ekonominin en dinamik bileşenlerinden biri olarak uluslararası ulaşım ağlarının sürekliliğini sağlayan stratejik bir konuma sahiptir. Ancak sektörün yüksek enerji tüketimi, yoğun operasyonel gereksinimleri ve atmosfere saldığı CO_2 emisyonları, onu sürdürülebilirlik tartışmalarının merkezine yerleştirmektedir. İklim değişikliğine olan etkilerinin giderek belirginleşmesi, hava yolu şirketlerinin çevresel, sosyal ve yönetişim (ÇSY) performanslarını yalnızca kurumsal bir sorumluluk alanı olmaktan çıkararak stratejik bir zorunluluk hâline getirmiştir. Emisyon azaltımı, yakıt verimliliği ve maliyet etkinlik gibi konular sürdürülebilirliğin çevresel ve ekonomik boyutunu, yolcu memnuniyeti, çalışanların sağlığı ve toplumla kurulan uyumlu ilişkiler sosyal boyutu olup sektörün başarısını doğrudan etkilemektedir. (Akduman vd., 2025) Uluslararası Hava Taşımacılığı Birliği (IATA), 2050 yılına kadar net sıfır karbon emisyonuna ulaşma hedefini ortaya koymuştur (IATA, 2023). Bu kapsamda, şirketlerin sürdürülebilirlik performanslarının çok boyutlu, nesnel ve yıllar arası karşılaştırılabilir yöntemlerle değerlendirilmesi, hem karar vericiler hem de sektör paydaşları açısından kritik önem taşımaktadır.

Bu araştırma, uluslararası havacılık sektöründe faaliyet gösteren 5 hava yolu şirketinin (Türk Hava Yolları, Lufthansa Airlines, Copa Airlines, Singapore Airlines ve Qatar Airways) 2020–2023 yılları arasındaki sürdürülebilirlik performanslarını ÇSY boyutları çerçevesinde çok kriterli karar verme (ÇKKV) yöntemlerini kullanarak kapsamlı biçimde analiz etmeyi amaçlamaktadır. Bu çalışma, hava yolu şirketlerinin sürdürülebilirlik göstergelerini çok boyutlu ve ölçülebilir bir analitik çerçeveye oturtmayı amaçlamaktadır. Ayrıca MEREC, MABAC ve MARCOS yöntemleri kullanılarak şirketlerin yıllık performans sıralamaları karşılaştırmalı biçimde değerlendirilmektedir. Son olarak, yıllar arasındaki performans değişimleri incelenerek şirketlerin sürdürülebilirlik stratejilerindeki eğilimler, gelişim alanları ve dönemsellik etkileri analiz edilmektedir.

Literatürde sıkça karşılaşılan sübjektif ağırlıklandırma yöntemlerinin aksine, bu çalışmada kriter ağırlıkları MEREC yöntemi ile belirlenmiş ve böylece veri odaklı, nesnel bir değerlendirme yaklaşımı benimsenmiştir. Belirlenen ağırlıkların hem MABAC hem de MARCOS yöntemlerine entegre edilmesi, farklı karar verme algoritmalarının sonuçlar üzerindeki tutarlılığını ve duyarlılığını karşılaştırmaya imkan tanıyan bütüncül bir analiz yapısı sunmuştur. Bu yönüyle araştırma, hava yolu şirketlerinin çevresel, sosyal ve yönetişim (ÇSY) performanslarındaki zaman içindeki değişimi güçlü bir yöntemsel temele dayandırarak incelemektedir. Sektör paydaşları ile yatırımcılar için güvenilir ve uygulanabilir sonuçlar sunmaktadır.

Uluslararası düzenlemeler, yatırımcı beklentileri ve kamuoyu duyarlılığı, hava yolu şirketlerinin sürdürülebilirlik performanslarını düzenli olarak izleme, değerlendirme ve iyileştirme gerekliliğini artırmaktadır. Dolayısıyla, hem çok boyutlu ÇSY kriterlerini dikkate alan hem de yıllar bazında karşılaştırılabilir sonuçlar sunabilen analitik bir metodolojiye duyulan ihtiyaç günden güne daha belirgin hâle gelmektedir. Bu çalışma, söz konusu ihtiyacı karşılamak amacıyla, farklı coğrafi, ekonomik ve operasyonel koşullara sahip hava yolu şirketlerinin sürdürülebilirlik performanslarını ortak bir ÇKKV yapısı altında karşılaştırılabilir şekilde analiz etmektedir.

Analiz sürecinde, hava yolu şirketlerine ait verilerin kamuya açık sürdürülebilirlik ve finansal raporlarda doğru, erişilebilir ve tutarlı biçimde sunulduğu varsayılmıştır. Ayrıca, pandemi döneminin yol açtığı operasyonel dalgalanmalara rağmen yıllar arası karşılaştırılabilirliğin korunduğu ve tüm şirketlerin aynı kriter seti altında değerlendirilebilir olduğu kabul edilmiştir.

Bu varsayımlar doğrultusunda çalışma, havacılık sektörünün sürdürülebilirlik performansını kapsamlı bir yöntemsel çerçeve ile inceleyerek literatüre hem içerik hem de metodoloji açısından katkı sunmayı hedeflemektedir.

2. LİTERATÜR TARAMASI

Son yıllarda çok kriterli karar verme (ÇKKV) yöntemleri, ekonomik, çevresel ve yönetsel alanlarda karar süreçlerini destekleyen güçlü araçlar olarak öne çıkmaktadır. Bu bağlamda yapılan çalışmalar, farklı sektörlerde nesnel ağırlıklandırma yöntemlerinin ve entegre modellerin kullanımına yönelik önemli katkılar sunmaktadır.

Duran (2023), N-11 ülkelerinin tedarik zinciri dayanıklılığını FM Global'in Küresel Dayanıklılık Endeksi verilerini kullanarak değerlendirmiştir. MEREC yöntemiyle kriter ağırlıklarını belirlemiş; EDAS, MARCOS ve WASPAS yöntemleriyle ülkelerin dayanıklılık performanslarını sıralamış ve sonuçları BORDA yöntemiyle bütünleştirmiştir. Analiz bulgularına göre "Tedarik Zinciri Görünürlüğü" ve "Kurumsal Yönetim" en etkili göstergeler olarak tanımlanmış; Güney Kore ve Türkiye en dayanıklı ülkeler olarak öne çıkmıştır. Bu çalışma, ÇKKV yöntemlerinin entegrasyonu yoluyla ulusal düzeyde tedarik zinciri dayanıklılığının ölçülmesine yönelik özgün bir yaklaşım sunmaktadır.

Benzer şekilde, Sümerli Sarıgül vd. (2023) havalimanı hizmet kalitesini değerlendirmek amacıyla MEREC tabanlı MARCOS ve CoCoSo yöntemlerini entegre eden yeni bir ÇKKV modeli geliştirmiştir. Skytrax'ın 2021 yılı verilerine dayanan çalışmada 17 havalimanı, 11 hizmet kriterine göre analiz edilmiştir. Bulgular, ulaşım hizmetleri, güvenlik hizmetleri ve terminal tesislerinin hizmet kalitesini en çok etkileyen unsurlar olduğunu göstermiştir. Sonuç olarak Chubu Centrair Havalimanı en yüksek, Tokyo Haneda Havalimanı ise en düşük hizmet kalitesine sahip olarak belirlenmiştir.

Meral (2023) ise BRICS-T ülkelerinin inovasyon performanslarını, Küresel İnovasyon Endeksi verilerine alternatif bir yaklaşımla değerlendirmiştir. Kriter ağırlıkları MEREC yöntemiyle belirlenmiş, ülke sıralamaları MARCOS yöntemiyle yapılmıştır. Sonuçlara göre en önemli kriterler "yatırımlar", "AR-GE" ve "çevrimiçi yaratıcılık" olarak tespit edilmiş; "politik çevre" ve "bilgi ve iletişim teknolojileri" en az etkili faktörler olmuştur. Genel sıralamada Çin ve Hindistan en yüksek, Brezilya ve Güney Afrika en düşük inovasyon performansına sahipken; Türkiye üçüncü sırada yer almıştır.

Sürdürülebilirlik temalı araştırmalarda da benzer yöntemsel eğilimler gözlenmektedir. Mondal vd. (2024), sürdürülebilir orman kaynaklarının yönetimi için Pythagorean bulanık MEREC–MARCOS modeline dayalı yeni bir ÇKKV yaklaşımı geliştirmiştir. Sekiz farklı orman yönetim modeli, odun üretimi, biyolojik çeşitlilik, hasat maliyeti ve yeniden ağaçlandırma giderleri gibi göstergelerle değerlendirilmiştir. Analiz sonucunda on yıllık periyotlu modelin (M1) en yüksek sürdürülebilirlik performansına sahip olduğu belirlenmiştir. Bu çalışma, belirsizliklerin azaltılmasına ve sürdürülebilir orman yönetiminde optimal model seçimine katkı sunmaktadır.

Benzer şekilde Sönmez ve Doğan (2024), OECD ülkelerinin çevresel performanslarını MEREC ve MARCOS yöntemleriyle incelemiştir. Çevresel sağlık, ekosistem canlılığı, karbon emisyonu ve yenilenebilir enerji kullanımı gibi göstergeler dikkate alınmıştır. Sonuçlara göre İsveç, Norveç ve İsviçre en yüksek çevresel performansa sahip ülkeler olurken; Türkiye ve

Meksika alt sıralarda yer almıştır. Bu bulgular, sürdürülebilirlik politikalarının güçlendirilmesi gerekliliğine işaret etmektedir.

Finansal performans analizleri kapsamında, Bektaş (2023) Borsa İstanbul (BİST) 100 endeksinde işlem gören enerji firmalarının 2022 yılı performanslarını MEREC–MABAC entegrasyonu ile değerlendirmiştir. Yedi finansal kriter üzerinden yapılan analizde, "Hisse Başına Kâr Oranı", "Toplam Duran Varlıklar" ve "Toplam Öz Kaynaklar" en önemli göstergeler olarak belirlenmiştir. ENJSA, AKSEN ve ZOREN firmaları en yüksek finansal performansa sahip firmalar olarak öne çıkmıştır. Benzer biçimde Ateş ve Koca (2024), Avrupa Birliği'nin Sınırda Karbon Düzenleme Mekanizması (CBAM) kapsamında çimento sektöründeki firmaların finansal performanslarını MEREC–MABAC yöntemiyle incelemiş; aktif kârlılığı, öz sermaye kârlılığı ve net kâr marjını en kritik kriterler olarak saptamıştır. Bulgular, CBAM'ın yürürlüğe girmesiyle firmaların çevresel ve finansal stratejilerini yeniden yapılandırmaları gerektiğini ortaya koymaktadır.

Karakuş (2023) çalışmasında, Türk Hava Yolları'nın 2014–2021 yıllarına ait sürdürülebilirlik raporlarını içerik analiziyle inceleyerek raporların yapısal ve içeriksel değişimlerini değerlendirmiştir. Bulgular, raporların görsel açıdan başarılı ancak içerik bakımından tutarsızlıklar ve izlenebilirlik sorunları barındırdığını göstermektedir. Bu durum, havacılık sektöründe sürdürülebilirlik raporlamasının şeffaflık, güvenilirlik ve denetlenebilirlik ilkeleri çerçevesinde geliştirilmesi gerektiğine işaret etmektedir.

Örgütsel davranış alanında, Yavuz ve Lale (2024) liyakat ve sadakat arasındaki ilişkiyi kavramsal ve nitel bir yaklaşımla ele almışlardır. Çalışma, liyakatin adalet ve çalışan bağlılığı üzerindeki olumlu etkilerini vurgulamakta; örgütlerin uzun vadeli başarısının adil ve eşitlikçi uygulamalarla sağlanabileceğini göstermektedir. Böylece etik ve performans temelli bir yönetim anlayışının gerekliliği ortaya konmuştur.

Dış politika bağlamında Özdilek (2025), ABD'nin vekil aktör stratejisini PYD-YPG örneği üzerinden analiz etmiştir. Nitel bir araştırma tasarımıyla yürütülen çalışma, vekil aktör kullanımının bölgesel istikrarı zayıflattığını ve uluslararası hukukun sınırlarını esnettiğini ortaya koymuştur. Bu analiz, vekil aktör stratejisinin küresel güvenlik dengeleri üzerindeki uzun vadeli etkilerine dair önemli bir değerlendirme sunmaktadır.

Son olarak, Ayçin ve Arsu (2021) Sosyal Gelişme Endeksi (SGE) göstergelerinin eşit ağırlıklandırılmasının ülkeler arası farklılıkları yansıtmadığı varsayımından hareketle, göstergelerin ağırlıklarını MEREC yöntemiyle belirleyip MARCOS yöntemiyle ülke sıralamalarını yeniden yapmıştır. Analiz sonucunda kapsayıcılık, sağlık ve ileri düzey eğitime erişim en önemli kriterler olarak bulunmuş; Norveç, Finlandiya ve Danimarka en yüksek sosyal gelişim performansına sahip ülkeler olarak öne çıkmıştır. Elde edilen bulgular, objektif ağırlıklandırma yaklaşımlarının ülke sıralamalarında anlamlı farklar yaratabileceğini göstermektedir.

Çalışmalara ait literatür taraması özeti Tablo 1' de verilmiştir.

Tablo 1. Literatür Taraması Özeti

Yazar (Yıl)	Uygulama Alanı	ÇKKV Yöntemi
Duran (2023)	N-11 ülkelerinde tedarik zinciri dayanıklılığı analizi	MEREC, EDAS, MARCOS, WASPAS, BORDA
Sümerli Sarıgül vd. (2023)	Havalimanı hizmet kalitesi değerlendirmesi	MEREC, MARCOS, CoCoSo
Meral (2023)	BRICS-T ülkelerinde inovasyon performansının değerlendirilmesi	MEREC, MARCOS
Mondal vd. (2024)	Sürdürülebilir orman kaynaklarının yönetiminde model seçimi	Pythagorean Bulanık MEREC, MARCOS
Sönmez ve Doğan (2024)	OECD ülkelerinin çevresel performans analizi	MEREC, MARCOS
Bektaş (2023)	Borsa İstanbul'daki enerji firmalarının finansal performans değerlendirmesi	MEREC, MABAC
Ateş ve Koca (2024)	CBAM kapsamında çimento sektöründeki firmaların finansal performans analizi	MEREC, MABAC
Karakuş (2023)	Türk Hava Yolları'nın sürdürülebilirlik raporlarının içerik analizi	İçerik Analizi (nitel yaklaşım)
Yavuz ve Lale (2024)	Örgütlerde liyakat–sadakat ilişkisi, örgütsel adalet	Kavramsal ve nitel analiz
Özdilek (2025)	ABD dış politikasında vekil aktör stratejisi	Nitel analiz, stratejik inceleme
Ayçin ve Arsu (2021)	Sosyal Gelişme Endeksi göstergeleriyle ülke sıralaması	MEREC, MARCOS

3. YÖNTEM VE MATERYAL

Bu bölümde analizde kullanılan veri seti ile uygulanan yöntemlere ilişkin ayrıntılı bilgiler sunulmuştur. Çalışmada, havayolu şirketlerinin sürdürülebilirlik performanslarını değerlendirmek amacıyla iki farklı ağırlıklandırma yaklaşımı ve bu yaklaşımlara entegre edilen iki çok kriterli karar verme (ÇKKV) yöntemi kullanılmıştır. İlk olarak, kriterlerin önem ağırlıklarını belirlemek için objektif ağırlıklandırma yöntemi olan MEREC yöntemi uygulanmıştır. MEREC yöntemiyle elde edilen kriter ağırlıkları, daha sonra MABAC ve MARCOS yöntemlerine entegre edilerek şirketlerin sürdürülebilirlik performans skorları hesaplanmış ve sıralamaları oluşturulmuştur.

İkinci aşamada ise yöntemin kararlılığını test etmek amacıyla alternatif bir ağırlıklandırma tekniği olan Entropi yöntemi kullanılarak aynı analiz süreci tekrarlanmıştır. Entropi tabanlı MABAC ve MARCOS sonuçları elde edilmiştir. Böylece MEREC ve Entropi tabanlı modeller karşılaştırılmış ve yöntemin duyarlılığını değerlendirmek için bir duyarlılık analizi gerçekleştirilmiştir.

Son aşamada, yöntemler arasında tutarlılığı ölçmek amacıyla MEREC tabanlı ve Entropi tabanlı sonuçlar Spearman korelasyon analizi ile karşılaştırılmış ve iki model arasında anlamlı bir sıralama ilişkisi olup olmadığı istatistiksel olarak test edilmiştir.

3.1. MEREC Yöntemi

MEREC yöntemi Mehdi Keshavarz-Ghorabaee, Maghsoud Amiri, Edmundas Kazimieras Zavadskas, Zenonas Turskis ve Jurgita Antuchevičienė tarafından geliştirilmiş ve 2021 yılında literatüre tanıtılmıştır. MEREC, kriter ağırlıklarını belirlemede kullanılan nesnel ağırlıklandırma teknikleri arasında yer alan bir yöntemdir. Her bir kriterin alternatiflerin genel performansı üzerindeki etkisini esas alarak ağırlıkları hesaplamaktadır. Alternatiflerin performansını daha fazla etkileyen kriterlere, yöntem gereği daha yüksek ağırlıklar atanmaktadır.

MEREC yöntemi, uygulama aşamasında altı temel adımdan oluşan bir süreç izlemektedir (Keshavarz-Ghorabaee vd. 2021).

Adım 1: Karar Matrisinin Oluşturulması

Alternatiflerin her bir kritere ilişkin değerlerini içeren karar matrisi oluşturulur. Karar matrisinde kullanılan x_{ij} elemanlarının sıfırdan büyük olması gerekir ($x_{ij} > 0$). Negatif herhangi bir veri bulunuyorsa uygun bir dönüştürme yöntemiyle pozitife çevrilir. n adet alternatif ve m adet kriterden oluşan karar matrisi Eşitlik (1)'de yer almaktadır.

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1j} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{1j} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{i1} & x_{i1} & \cdots & x_{ij} & \cdots & x_{im} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nj} & \cdots & x_{nm} \end{bmatrix} \quad (1)$$

Adım 2: Karar Matrisinin Normalize Edilmesi

Matriste yer alan değerlerin ortak bir ölçeğe taşınabilmesi için basit bir doğrusal normalizasyon yöntemi kullanılır. Normalize edilen matristeki her bir değer n_{xij} şeklinde gösterilir. B fayda (yarar) yönlü kriterleri, H ise maliyet (yarar olmayan) yönlü kriterleri göstermektedir. Normalizasyon işlemi içi formül Eşitlik (2)'de verilmiştir.

$$n_{ij}^{x} = \begin{cases} \dfrac{\min\limits_{k} x_{kj}}{x_{ij}}, & j \in B \\ \dfrac{x_{ij}}{\max\limits_{k} x_{kj}}, & j \in H \end{cases} \quad (2)$$

Adım 3: Genel Performans Değerlerinin (S_i) Elde Edilmesi

Alternatiflerin genel performanslarını belirlemek için tüm kriterlere eşit ağırlık veren logaritmik bir performans ölçütü kullanılmaktadır. Bir önceki adımda hesaplanan normalize değerler dikkate alındığında, n_{xij} değerinin küçülmesi ilgili alternatifin performansını (S_i) artıran bir etki yaratır. Bu kapsamda genel performansların hesaplanmasında Eşitlik (3)'de verilen ifade kullanılmaktadır.

$$S_i = ln\left(1 + \left(\frac{1}{m}\sum_j \left|ln\left(n_{ij}^{x}\right)\right|\right)\right) \quad (3)$$

Adım 4: Kriter Değeri Hariç Tutularak Genel Performans Değerlerinin (S'_{ij}) Elde Edilmesi

Bu adımda, bir önceki adımda kullanılan logaritmik performans ölçütü benzer şekilde uygulanır. Ancak bu adım ile üçüncü adım arasındaki temel fark, performansların her bir kriter ayrı ayrı çıkarılarak hesaplanmasıdır. Bu nedenle, m kriter için m farklı performans seti elde edilir. S_{ij}, i. alternatife ait genel performansın, j. kriter çıkarıldığında aldığı değeri ifade etmektedir. Bu hesaplamaların yapılmasında aşağıdaki eşitlik kullanılır.

Bu adım ile üçüncü adım arasındaki temel fark, performansların her kriterin ayrı ayrı çıkarılarak hesaplanmasıdır. Dolayısıyla m kriter için m farklı performans seti oluşur. Bu kapsamda S_{ij}, i. alternatife ait performansın, j. kriter çıkarıldığında aldığı değeri göstermektedir. Performans değerleri Eşitlik (4)'de verilen matematiksel formülasyon üzerinden hesaplanmaktadır.

$$S'_{ij} = ln\left(1 + \left(\frac{1}{m}\sum_{k,k\neq j}|ln(n_{ik}^{x})|\right)\right) \quad (4)$$

Adım 5: Mutlak Sapmalar Toplamının (E_j) Elde Edilmesi

Her bir kriterin çıkarılmasının alternatiflerin performansları üzerindeki etkisi, önceki adımlarda elde edilen genel ve kriter çıkarılmış performans değerleri kullanılarak hesaplanır. E_j ile, j. kriterin çıkarılmasının yarattığı etki ifade edilmektedir ve bu etki Eşitlik (5)'deki matematiksel formül üzerinden hesaplanır.

$$E_j = \sum_i |S'_{ij} - S_i| \quad (5)$$

Adım 6: Kriter Önem Ağırlıklarının (w_j) Elde Edilmesi

Eşitlik (6) ile her kriterin önem ağırlıkları hesaplanır.

$$w_j = \frac{E_j}{\sum_k E_k} \quad (6)$$

3.2. MABAC YÖNTEMİ

MABAC yöntemi Dragan Pamučar ve Zoran Ćirović tarafından geliştirilmiş ve 2015 yılında literatüre tanıtılmıştır. İlk uygulaması ve tanıtımıyla birlikte, MABAC "çok kriterli, nitelikli karar verme" problemlerinde referans bölgelerin kullanıldığı bir yaklaşım getirmiştir. Temelde bu yöntem, her alternatifin kriter fonksiyonunun sınır yaklaşım alanı ile ilişkilendirilmiş ideal/anti-ideal referans çözümlerine ne kadar yakın olduğunu değerlendirir. Yani alternatifleri, sınır yaklaşım alanlarına göre olan uzaklıklarına göre sıralar.

MABAC yöntemi, uygulama aşamları birbirini takip eden altı adımdan oluşmaktadır (Pamučar ve Ćirović, 2015).

Adım 1: Karar Matrisinin Oluşturulması

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (7)$$

m adet alternatifin n adet kriter doğrultusunda değerlendirilmesi gerekmektedir. Alternatifler, $A_i = (x_{i1}, x_{i2}, \ldots, x_{in})$ vektörleri ile gösterilir ve burada x_{ij}, i'inci alternatifin j'inci kritere göre değerini ifade eder (i = 1, 2, …, m; j = 1, 2, …, n). Ayrıca, m alternatif sayısını, n ise kriterlerin toplam sayısını temsil etmektedir.

Adım 2: Karar Matrisinin Normalize Edilmesi

$$N = \begin{bmatrix} n_{11} & n_{12} & \cdots & n_{1n} \\ n_{21} & n_{22} & \cdots & n_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ n_{m1} & n_{m2} & \cdots & n_{mn} \end{bmatrix} \quad (8)$$

Normalize edilmiş matrisin (N) elemanları, kriter türüne bağlı olarak aşağıdaki eşitlikler kullanılarak hesaplanır.

(a) Fayda tipi kriterler için (kriterin daha yüksek değeri tercih edilir)

$$n_{ij} = \frac{x_{ij} - x_i^-}{x_i^+ - x_i^-} \quad (9)$$

(b) Maliyet tipi kriterler için (kriterin daha düşük değeri tercih edilir)

$$n_{ij} = \frac{x_{ij} - x_i^+}{x_i^- - x_i^+} \quad (10)$$

x_{ij}, başlangıç karar matrisindeki ilgili elemanı temsil ederken, x_i^+ ve x_i^- şu şekilde tanımlanır:

$x_i^+ = max(x_1, x_1, \ldots, x_m) \rightarrow$ i'inci kriter için alternatifler arasında gözlemlenen en yüksek değer

$x_i^- = min(x_1, x_1, \ldots, x_m) \rightarrow$ i'inci kriter için alternatifler arasında gözlemlenen en düşük değer

Adım 3: Ağırlıklandırılmış Matrisin Oluşturulması

Ağırlıklandırılmış matrisin her bir elemanı Eşitlik (11) kullanılarak hesaplanır.

$$v_{ij} = w_i \times (n_{ij} + 1) \quad (11)$$

n_{ij} normalize matrisin (N) elemanlarını, w_i ise kriterlerin ağırlık katsayılarını göstermektedir. V matrisi Eşitlik (12) kullanılarak şu şekilde ifade edilir:

$$V = \begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1n} \\ v_{21} & v_{22} & \cdots & v_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ v_{m1} & v_{m2} & \cdots & v_{mn} \end{bmatrix} = \begin{bmatrix} w_1 \times (n_{11} + 1) & w_2 \times (n_{12} + 1) & \cdots & w_n \times (n_{1n} + 1) \\ w_1 \times (n_{21} + 1) & w_2 \times (n_{22} + 1) & \cdots & w_n \times (n_{2n} + 1) \\ \vdots & \vdots & \ddots & \vdots \\ w_1 \times (n_m + 1) & w_2 \times (n_{m2} + 1) & \cdots & w_n \times (n_{mn} + 1) \end{bmatrix} \quad (12)$$

n toplam kriter sayısını, m toplam alternatif sayısını ifade etmektedir.

Adım 4: Sınır Yakınlık Alan Matrisinin Oluşturulması

$$g_i = \left(\prod_{j=1}^{m} v_{ij}\right)^{1/m} \quad (13)$$

v_{ij}, ağırlıklandırılmış matrisin elemanlarını ve m alternatif sayısını temsil etmektedir. Tüm kriterler için g_i değeri belirlendikten sonra, alternatiflerin değerlendirilmesinde kullanılacak kriter sayısına (n) bağlı olarak $n \times 1$ boyutunda sınır yaklaşım alanı matrisi G oluşturulur.

$$G = [g_1 \quad g_2 \quad \cdots \quad g_n] \quad (14)$$

Adım 5: Alternatiflerin Sınır Yakınlık Alanından Uzaklıklarının Saptanması

$$Q = \begin{bmatrix} q_{11} & q_{12} & \cdots & q_{1n} \\ q_{21} & q_{22} & & q_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ q_{m1} & q_{m2} & \cdots & q_{mn} \end{bmatrix} \quad (15)$$

Her bir alternatif için sınır yaklaşım alanından olan uzaklık (q_{ij}), ağırlıklandırılmış matrisin (V) elemanları ile sınır yaklaşım alanı (G) değeri arasındaki fark temel alınarak belirlenmektedir. Bu şekilde, alternatiflerin her bir kriter açısından sınır yaklaşım alanına olan mesafeleri Q matrisi içinde ifade edilmektedir.

$$Q = V - G = \begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1n} \\ v_{21} & v_{22} & & v_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ v_{m1} & v_{m2} & \cdots & v_{mn} \end{bmatrix} - \begin{bmatrix} g_1 & g_2 & \cdots & g_n \\ g_1 & g_2 & & g_n \\ \cdots & \cdots & \cdots & \cdots \\ g_1 & g_2 & \cdots & g_n \end{bmatrix} \quad (16)$$

$$Q = \begin{bmatrix} v_{11} - g_1 & v_{12} - g_2 & \cdots & v_{1n} - g_n \\ v_{21} - g_1 & v_{22} - g_2 & \cdots & v_{2n} - g_n \\ \cdots & \cdots & \cdots & \cdots \\ v_{m1} - g_1 & v_{m2} - g_2 & \cdots & v_{mn} - g_n \end{bmatrix} = \begin{bmatrix} q_{11} & q_{12} & \cdots & q_{1n} \\ q_{21} & q_{22} & & q_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ q_{m1} & q_{m2} & \cdots & q_{mn} \end{bmatrix} \quad (17)$$

Her bir kriter için sınır yaklaşım alanı q_i, ağırlıklandırılmış matrisin elemanları v_{ij}, kriter sayısı n ve alternatif sayısı m kullanılarak tanımlanmaktadır. Alternatifler, sınır yaklaşım alanı (G), üst yaklaşım alanı (G^+) veya alt yaklaşım alanı (G^-) içinde yer alabilir; A_i bu üç alandan birine dahil olmaktadır. Üst yaklaşım alanı (G^+), ideal alternatifi (A^+) kapsarken; alt yaklaşım alanı (G^-), anti-ideal alternatifi (A^-) içerir. Alternatifin hangi yaklaşım alanına ait olduğu, ilgili matematiksel ifade olan Eşitlik (18) temel alınarak belirlenmektedir.

$$A_i \in \begin{cases} G^+ & if \quad q_{ij} > 0 \\ G & if \quad q_{ij} = 0 \\ G^- & if \quad q_{ij} < 0 \end{cases} \quad (18)$$

Bir alternatifin en iyi seçenek olarak belirlenebilmesi için, mümkün olan en fazla sayıda kriterinin üst yaklaşım alanına (G^+) dahil olması gerekmektedir. Örneğin, bir alternatif 6 kriter üzerinden değerlendiriliyorsa ve 5 kriteri üst yaklaşım alanına, 1 kriteri alt yaklaşım alanına (G^-) ait ise; bu durumda alternatifin 5 kriter açısından ideal alternatife oldukça yakın olduğu, bir kriter açısından ise anti-ideal alternatife yakın olduğu anlaşılmaktadır.

Eğer $q_{ij} > 0$ ve dolayısıyla $q_{ij} \in G^+$, alternatif A_i ideal alternatife yakın veya eşit olmaktadır. Eğer $q_{ij} < 0$ ve dolayısıyla $q_{ij} \in G^-$, alternatif A_i anti-ideal alternatife yakın veya olmaktadır.

Adım 6: Alternatiflere ait Kriter Fonksiyonlarının Hesaplanması ve Sıralanması

Eşitlik (19)'da verilen her bir alternatifin kriter fonksiyonunun değeri, söz konusu alternatifin sınır yaklaşım alanlarından olan uzaklıklarının q_{ij} toplamı alınarak hesaplanmaktadır.

$$S_i = \sum_{j=1}^{n} q_{ij}, \quad j = 1, 2, \ldots, n, \; i = 1, 2, \ldots, m \quad (19)$$

Burada, n toplam kriter sayısını, m ise alternatif sayısını göstermektedir. Bu değerler kullanılarak alternatifler sıralanır ve en uygun seçenek belirlenmektedir.

3.3. MARCOS YÖNTEMİ

MARCOS yöntemi ilk olarak Željko Stević ve arkadaşları tarafından tanımlanmıştır. Çok kriterli karar verme yöntemlerinden biri olan MARCOS, alternatiflerin ideal ve anti-ideal

çözümlerle karşılaştırılması prensibine dayanır. AHP, TOPSIS veya VIKOR yöntemlerine benzer olan MARCOS yöntemi uzlaşma çözümünü temel alması ile öne çıkmaktadır (Stanković vd., 2020).

MARCOS yöntemi uygulama adımları sırasıyla verilmiştir.

Adım 1: Karar Matrisinin Oluşturulması

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (20)$$

Adım 2: Genişletilmiş Karar Matrisinin Oluşturulması

Anti ideal (AAI) ve ideal (AI) çözümün tanımlanmasıyla gerçekleştirilen genişletilmiş bir karar matrisi oluşturulur.

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \\ x_{aai1} & x_{aai2} & \cdots & x_{aain} \\ x_{ai1} & x_{ai2} & \cdots & x_{ain} \end{bmatrix} \quad (21)$$

AAI, alternatifler arasındaki en kötü alternatifi temsil ederken; AI, en iyi alternatifi göstermektedir. Kriterlerin yapısına bağlı olarak, AAI ve AI değerleri (22) ve (23) numaralı eşitlikler temel alınarak hesaplanmaktadır.

$$AAI = \min_i x_{ij} \; if \; j \in B \; and \; \max_i x_{ij} \; if \; j \in C \quad (22)$$

$$AAI = \max_i x_{ij} \; if \; j \in B \; and \; \min_i x_{ij} \; if \; j \in C \quad (23)$$

B kriteri maksimizasyon, C kriteri ise minimizasyon grubuna aittir.

Adım 3: Genişletilmiş Karar Matrisinin Normalize Edilmesi

$$n_{ij} = \frac{x_{ai}}{x_{ij}} \; if \; j \in C \quad (24)$$

$$n_{ij} = \frac{x_{ij}}{x_{ai}} \; if \; j \in B \quad (25)$$

x_{ij} ve x_{ai} terimleri, X matrisinin elemanlarını ifade etmektedir.

Adım 4: Genişletilmiş Karar Matrisinin Ağırlıklandırılması

$$v_{ij} = n_{ij} \times w_{ij} \quad (26)$$

Adım 5: Fayda Derecelerinin (K_i) Hesaplanması

$$K_i^- = \frac{S_i}{S_{aai}} \quad (27)$$

$$K_i^+ = \frac{S_i}{S_{ai}} \quad (28)$$

S_i (i = 1, 2, …, m), V matrisinin elemanlarının toplamını ifade etmektedir. Bu ifade Eşitlik (29)'de verilmiştir.

$$S_i = \sum_{i=1}^{n} v_{ij} \quad (29)$$

Adım 6: Alternatiflerin Fayda Fonksiyonlarının $f(K_i)$ Belirlenmesi ve Sıralanması

$$f(K_i) = \frac{K_i^+ + K_i^-}{1 + \frac{1-f(K_i^+)}{f(K_i^+)} + \frac{1-f(K_i^-)}{f(K_i^-)}}; \quad (30)$$

$f(K_i^-)$ AAI'ye (en kötü alternatif) ilişkin fayda fonksiyonunu, $f(K_i^+)$ ise AI'ye (en iyi alternatif) ilişkin fayda fonksiyonunu temsil etmektedir.

AI ve AAI çözümlerine ilişkin fayda fonksiyonlarının belirlenmesinde Eşitlik (31) ve (32) kullanılmıştır.

$$f(K_i^-) = \frac{K_i^+}{K_i^+ + K_i^-} \quad (31)$$

$$f(K_i^+) = \frac{K_i^-}{K_i^+ + K_i^-} \quad (32)$$

Ve alternatifler sıralanır.

4. BULGULAR

Çalışmada belirlenen alternatifler ve kriterler üzerinden MEREC, MABAC ve MARCOS yöntemlerinin uygulanması aşamaları bu bölümde detaylı olarak sunulmaktadır. Öncelikle, değerlendirme sürecinde kullanılan alternatifler ve kriterler tanımlanmış, ardından yöntemlerin adım adım uygulanmasıyla kriter ağırlıkları ve alternatiflerin sıralamaları elde edilmiştir.

4.1. Veri Seti ve Karar Matrisi

Çalışmada değerlendirilen alternatifler, havacılık sektörünün uluslararası arenada öncü ve büyük şirketlerinden çalışmanın kapsamına uygun olarak seçilmiş olup, her bir alternatifin performansı ÇSY boyutlarına göre belirlenen etkin kriterler üzerinden analiz edilmiştir. Kriterler, hem niceliksel hem de niteliksel boyutları içermektedir. Sürdürülebilirliğin çevresel, sosyal ve yönetişim boyutları altında toplanmaktadır.

Çalışmada analize 5 hava yolu şirketi dahil edilmiştir. Sürdürülebilirlik performanslarının ölçülebilmesi amacıyla çevresel, ekonomik ve operasyonel boyutları kapsayan toplam 9 kriter belirlenmiştir. Çalışmada kullanılan hava yolu şirketleri ve bu şirketlere ilişkin genel bilgiler Tablo 2' de sunulmaktadır.

Tablo 2. Hava Yolu Şirketleri

No	Şirket Adı	Ülke	Çağrı Kodu	IATA Kodu	ICAO Kodu
1	Türk Hava Yolları	Türkiye	TURKISH	TK	THY
2	Lufthansa Hava Yolları	Almanya	LUFTHANSA	LH	DLH
3	Copa Hava Yolları	Panama	COPA	CM	CMP
4	Singapur Hava Yolları	Singapur	SINGAPORE	SQ	SIA
5	Qatar Hava Yolları	Qatar	QATARI	QR	QTR

- **Çevresel Kriterler**

Toplam CO_2 Emisyonu (milyon ton CO2e) (K1): Hava yolu şirketlerinin faaliyetlerinden kaynaklanan tüm sera gazı emisyonlarını kapsamaktadır. Scope 1 doğrudan uçuş operasyonlarından (uçak yakıtı tüketimi) kaynaklanan emisyonları, Scope 2 şirketin tükettiği

elektrik, ısıtma ve soğutma gibi enerji kaynaklı dolaylı emisyonları, Scope 3 ise tedarik zinciri, yer hizmetleri, yolcu taşımacılığına bağlı dolaylı faaliyetler ve iş seyahatleri gibi değer zinciri emisyonlarını ifade etmektedir. Emisyonlar yıllık olarak milyon ton CO_2 eşdeğeri (CO_2e) cinsinden raporlanır. Havacılık sektörü için Scope 1 emisyonları en büyük paya sahip olsa da, Scope 3 emisyonları da önemli bir kısmı oluşturmaktadır. Bu nedenle toplam CO_2 emisyonlarının bütünsel olarak dikkate alınması, şirketlerin iklim değişikliği üzerindeki gerçek etkisini yansıtan kritik bir göstergedir.

Yakıt Verimliliği (lt / 100 AKK) (K2): Hava yolu operasyonlarının çevresel etkinliğini ölçen kritik bir parametredir. Arz edilen koltuk-km (ASK) belirli bir mesafede taşınabilecek yolcu kapasitesini ifade eder. Bu kriter, 100 AKK başına tüketilen yakıt miktarını litre cinsinden gösterir. Verimliliğin yüksek olması, hem daha az yakıt tüketimi hem de daha düşük karbon salımı anlamına gelir. Bu nedenle kriter, hem çevresel hem de ekonomik performans göstergesi olarak çift yönlü önem taşır.

Yolcu Doluluk Oranı (%) (K3): Taşınan yolcu-km'nin (RPK) arz edilen koltuk-km'ye (ASK) oranını ifade eder. Yüzdesel olarak hesaplanan bu oran, hava yolu şirketlerinin kapasite kullanım etkinliğini gösterir. Yüksek doluluk oranı, uçuş başına düşen emisyon miktarını düşürdüğü için çevresel verimlilik üzerinde olumlu etki yaratır. Ayrıca işletme gelirlerinin artmasına katkı sağlar.

Yolcuların Satın Aldığı Km (RPK, Milyon) (K4): Revenue Passenger Kilometer (RPK), yolcular tarafından satın alınan koltuk-km'lerin toplamıdır ve milyon yolcu-km olarak ölçülür. Bu kriter, hava yolu şirketinin operasyonel ölçeğini yansıtır. Şirketin toplam yolcu talebini ve gelir potansiyelini gösterirken aynı zamanda karbon ve yakıt verimliliği hesaplarında temel parametrelerden biridir.

Filonun Ortalama Yaşı (Yıl) (K5): Şirketin kullandığı uçakların ortalama yaşını ifade eder. Uçakların yaşı arttıkça yakıt verimliliği düşmekte ve bakım maliyetleri artmaktadır. Yeni nesil uçaklar ise daha düşük emisyon ve yakıt tüketimi ile çevresel performansa katkı sağlamaktadır. Dolayısıyla filonun ortalama yaşı, çevresel sürdürülebilirlik açısından kritik bir gösterge olarak kabul edilmektedir.

- **Sosyal Kriterler**

Toplam Çalışan Sayısı (K6): Hava yolu şirketlerinin doğrudan sağladığı istihdamı gösteren bu kriter, sosyal sürdürülebilirliğin en temel ölçütlerinden biridir. Toplam çalışan sayısı, şirketin ölçeğini, insan kaynağı kapasitesini ve ekonomik katkısını göstermektedir. Ayrıca çalışan sayısı, şirketin iş gücü politikaları ve sosyal etkilerinin değerlendirilmesinde önemli bir rol oynamaktadır.

Kadın Çalışan Oranı (%) (K7): Şirketlerdeki toplumsal cinsiyet eşitliğini ve çeşitlilik düzeyini ortaya koyan kritik bir göstergedir. Bu oran, kadın çalışan sayısının toplam çalışan sayısına bölünmesiyle hesaplanır. Havayolu sektörü tarihsel olarak erkek egemen bir yapıya sahip olduğundan, kadın çalışan oranı sosyal sürdürülebilirliğin ve kapsayıcı istihdam politikalarının değerlendirilmesi açısından önemlidir.

- **Yönetişim Kriterleri**

Yönetim Kurulu Üye Sayısı (K8): Şirketin yönetim kurulunda görev yapan toplam üye sayısını ifade eder. Yönetim kurulu, şirketin stratejik karar alma mekanizmasının merkezinde yer alır. Üye sayısı, yönetim kurulunun büyüklüğünü ve karar alma süreçlerinin etkinliğini yansıtır. Kurumsal yönetişim kalitesinin önemli göstergelerinden biridir.

Yönetim Kurulu Kadın Üye Oranı (%) (K9): Yönetim kurulundaki kadın üyelerin toplam üyeler içindeki oranını ifade eder. Çeşitlilik, kapsayıcılık ve cinsiyet eşitliği açısından önemli bir göstergedir. Kadın üyelerin yönetim kurullarında daha fazla yer alması, farklı bakış açıları ve dengeli karar mekanizmaları oluşmasına katkı sağlar. Uluslararası kurumsal yönetişim standartlarında da bu kriter özel önem taşımaktadır.

Tablo 3' te hava yolu şirketlerine ait sürdürülebilirlik raporlarından elde edilen 2020-2023 yılı verileri sunulmuştur.

Tablo 3. Hava Yolu Şirketlerine Ait 2020-2023 Yılı Verileri

ÇSY BOYUTLARI		ÇEVRESEL					SOSYAL		YÖNETİŞİM	
Yıl	Havayolu	Toplam CO_2 Emisyonu (milyon ton CO2e)	Yakıt Tüketimi (lt / 100 AKK)	Yolcu Doluluk Oranı (%)	Yolcuların Satın Aldığı Km (RPK, Milyon Km)	Filonun Ortalama Yaşı (Yıl)	Toplam Çalışan Sayısı	Kadın Çalışan Oranı (%)	Yönetim Kurulu Üye Sayısı	Yönetim Kurulu Kadın Üye Oranı (%)
2020	THY	9.094.999	3,210	0,710	53.254	8,4	29.476	0,460	9	0,111
2021	THY	16.591.244	3,160	0,679	86.705	8,5	30.700	0,460	9	0,111
2022	THY	22.983.093	3,100	0,806	162.679	8,7	34.200	0,480	9	0,111
2023	THY	27.464.369	3,070	0,826	193.932	9,3	37.700	0,460	9	0,111
2020	Lufthansa	15.136.760	4,180	0,633	69.462	12,5	110.065	0,453	20	0,172
2021	Lufthansa	14.429.365	4,050	0,616	89.397	12,7	105.290	0,448	20	0,187
2022	Lufthansa	32.250.424	3,590	0,798	207.035	13,1	109.509	0,450	20	0,204
2023	Lufthansa	36.975.565	3,520	0,829	249.269	13,4	96.677	0,455	20	0,223
2020	Copa	886.303	9,889	0,628	7.555	9,0	5.797	0,315	11	0,182
2021	Copa	1.703.520	2,140	0,786	11.738	9,0	5.855	0,364	11	0,182
2022	Copa	2.802.373	2,257	0,851	20.790	9,5	6.057	0,340	11	0,182
2023	Copa	3.142.106	2,131	0,868	24.052	9,7	7.625	0,345	11	0,182
2020	Singapor	3.786.578	42,600	0,133	2.891	5,4	14.956	0,502	10	0,200
2021	Singapor	7.241.240	12,970	0,301	20.665	5,1	14.125	0,481	11	0,182
2022	Singapor	13.896.346	4,270	0,854	113.628	5,6	15.539	0,496	11	0,182
2023	Singapor	16.104.086	4,220	0,880	143.852	6,3	17.802	0,522	10	0,200
2020	Qatar	14.333.354	3,250	0,630	97.000	5,8	46.000	0,320	9	0,111
2021	Qatar	17.740.000	3,120	0,550	94.000	6,1	39.000	0,340	9	0,110
2022	Qatar	22.680.000	2,900	0,695	130.000	6,2	45.633	0,370	9	0,110
2023	Qatar	25.710.000	2,800	0,873	207.000	6,5	50.000	0,370	7	0,143

Her alternatifin, tüm kriterler doğrultusundaki verileri toplanmış ve başlangıç karar matrisi bu değerlere göre oluşturulmuştur. Bu yapı, MEREC yöntemi ile kriter ağırlıklarının belirlenmesi ve MABAC ile MARCOS yöntemleriyle alternatiflerin karşılaştırılmasına uygun bir temel sağlamaktadır.

Alternatifler (A): A1, A2, A3, A4, A5.

Kriterler (C): K1, K2, K3, K4, K5, K6, K7, K8, K9.

MEREC yöntemi ile kriter ağırlıklarının belirlenmesi ve MABAC ile MARCOS yöntemleri kullanılarak değerlendirme aşamaları, şirketlerin 2023 yılı verileri üzerinde örnek uygulama olarak gerçekleştirilmiştir.

4.2. MEREC ile Kriter Ağırlıkları Belirleme

Bu çalışmada kullanılan 9 kriterin ağırlıkları, MEREC yöntemi ile belirlenmiştir. 2023 yılına ait başlangıç karar matrisi Tablo 4' te gösterilmiştir.

Tablo 4. 2023 Yılı Başlangıç Karar Matrisi

	Min	Min	Mak	Mak	Min	Mak	Mak	Mak	Mak
	K1	K2	K3	K4	K5	K6	K7	K8	K9
A1	27,464	3,070	0,826	193932,000	9,300	37700,000	0,460	9,000	0,111
A2	36,976	3,520	0,829	249269,000	13,400	96677,000	0,455	20,000	0,223
A3	3,142	2,131	0,868	24052,000	9,700	7625,000	0,345	11,000	0,182

A4	16,104	4,220	0,880	143851,752	6,300	17802,000	0,522	10,000	0,200
A5	25,710	2,800	0,873	2070000,000	6,500	50000,000	0,370	7,000	0,143

Normalize karar matrisi Tablo 5'te verilmiştir.

Tablo 5. Normalize Edilmiş Matris

	Min	**Min**	**Mak**	**Mak**	**Min**	**Mak**	**Mak**	**Mak**	**Mak**
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**K7**	**K8**	**K9**
A1	0,743	0,727	0,938	0,778	0,694	0,390	0,881	0,450	0,498
A2	1,000	0,834	0,942	1,000	1,000	1,000	0,872	1,000	1,000
A3	0,085	0,505	0,986	0,096	0,724	0,079	0,661	0,550	0,815
A4	0,436	1,000	1,000	0,577	0,470	0,184	1,000	0,500	0,897
A5	0,695	0,664	0,993	0,830	0,485	0,517	0,709	0,350	0,641

Alternatiflere ait genel performans değerleri Tablo 6' da gösterilmiştir.

Tablo 6. Genel Performans Değerleri

	S_i
A1	0,357
A2	0,041
A3	0,725
A4	0,415
A5	0,382

Kriter Değeri Haricinde Genel Performans Değerleri Tablo 7' de gösterilmiştir.

Tablo 7. Kriter Değeri Haricinde Genel Performans Değerleri

S'_{ij}	**Min**	**Min**	**Mak**	**Mak**	**Min**	**Mak**	**Mak**	**Mak**	**Mak**
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**K7**	**K8**	**K9**
A1	0,333	0,332	0,352	0,337	0,328	0,281	0,347	0,293	0,301
A2	0,041	0,022	0,035	0,041	0,041	0,041	0,026	0,041	0,041
A3	0,582	0,687	0,724	0,590	0,707	0,578	0,702	0,692	0,714
A4	0,352	0,415	0,415	0,374	0,358	0,282	0,415	0,363	0,407
A5	0,354	0,351	0,382	0,368	0,326	0,331	0,356	0,299	0,348

Her bir kriterin mutlak sapmalar toplamı Tablo 8' de gösterilmiştir.

Tablo 8. Mutlak Sapmalar Toplamı

	K1	K2	K3	K4	K5	K6	K7	K8	K9
E_j	1,291	1,148	1,047	1,244	1,194	1,441	1,108	1,266	1,144

MABAC ve MARCOS yöntemlerinde kullanılacak kriter önem ağırlıkları Tablo 9' daki gibi bulunmuştur.

Tablo 9. Kriter Önem Ağırlıkları

W_j	0,1186	0,1055	0,0962	0,1143	0,1097	0,1324	0,1018	0,1164	0,1051

4.3. MABAC ile Değerlendirme

MEREC yöntemi ile bulunan kriter ağırlıkları MABAC yönteminde girdi olarak kullanılmış olup 2023 yılına ait veriler üzerinden değerlendirme yapılmıştır. 2023 yılına ait başlangıç karar matrisi Tablo 4'te gösterilmişti. MABAC yöntemi ile normalize edilmiş karar matrisi Tablo 10'da verilmiştir.

Tablo 10. Normalize Edilmiş Matris

	Min	Min	Mak	Mak	Min	Mak	Mak	Mak	Mak
	K1	K2	K3	K4	K5	K6	K7	K8	K9
A1	-21,279	-3,130	-0,938	169879,9	-6,227	30074,9	-0,546	1,650	-0,498
A2	-11,768	-2,680	-0,935	225216,9	-2,127	89051,9	-0,551	12,650	-0,386
A3	-45,601	-4,069	-0,896	-0,096	-5,827	-0,079	-0,661	3,650	-0,427
A4	-32,639	-1,980	-0,884	119799,7	-9,227	10176,9	-0,484	2,650	-0,409
A5	-23,033	-3,400	-0,891	182947,9	-9,027	42374,9	-0,636	-0,350	-0,466

MEREC yönteminden elde edilen kriter ağırlıkları kullanılarak ağırlıklandırılmış matris Tablo 11'de gösterilmiştir.

Tablo 11. Ağırlıklandırılmış Matris

	Min	Min	Mak	Mak	Min	Mak	Mak	Mak	Mak
	K1	K2	K3	K4	K5	K6	K7	K8	K9
A1	-2,406	-0,225	0,006	19417,361	-0,574	3982,869	0,046	0,308	0,053
A2	-1,277	-0,177	0,006	25742,372	-0,124	11793,027	0,046	1,588	0,065
A3	-5,291	-0,324	0,010	0,103	-0,530	0,122	0,035	0,541	0,060
A4	-3,753	-0,103	0,011	13693,197	-0,903	1347,833	0,053	0,425	0,062
A5	-2,614	-0,253	0,011	20911,032	-0,881	5611,724	0,037	0,076	0,056

Kriterlere ilişkin sınır yakınlık alan matrisi Tablo 12' de verilmiştir.

Tablo 12. Sınır Yakınlık Alan Matrisi

	K1	K2	K3	K4	K5	K6	K7	K8	K9
g_j	-31,891	0	0,0	2956157934596940,0	-0,006	86672537108	0,0	0,002	0,0

Kriterlerin sınır yakınlık alan matrisine uzaklıkları Tablo 13' te verilmiştir.

Tablo 13. Kriterlerin Sınır Yakınlık Alan Matrisine Uzaklıkları

S'_{ij}	Min	Min	Mak	Mak	Min	Mak	Mak	Mak	Mak
	K1	K2	K3	K4	K5	K6	K7	K8	K9
A1	29,5	0	0,01	-2956157934577520,0	-0,6	-8667253707	0,05	0,31	0,05
A2	30,6	0	0,01	-2956157934571200,0	-0,1	-8667253699	0,05	1,59	0,07
A3	26,6	0	0,01	-2956157934596940,0	-0,5	-8667253711	0,04	0,54	0,06
A4	28,1	0	0,01	-2956157934583250,0	-0,9	-8667253710	0,05	0,42	0,06
A5	29,3	0	0,01	-2956157934576030,0	-0,9	-8667253705	0,04	0,07	0,06

Alternatiflerin genel performans değerleri ve sıralamaları Tablo 14' te verilmiştir. En iyi performansı A2 şirketi gösterirken, en kötü performans A3 şirketine aittir.

Tablo 14. Genel Performans Değerleri

	S_{ij}	Sıralama
A1	-2964825188284340	**3**
A2	-2964825188270200	**1**
A3	-2964825188307740	**5**
A4	-2964825188292700	**4**
A5	-2964825188281220	**2**

4.4. MARCOS ile Değerlendirme

MEREC yönteminden elde edilen kriter ağırlıkları MARCOS yönteminde kullanılarak hava yolu şirketlerinin 2023 yılına ait verileri üzerinden değerlendirme yapılmıştır. Başlangıç karar matrisi Tablo 4'te gösterilmişti. Genişletilmiş karar matrisi Tablo 15' te gösterilmiştir.

Tablo 15. Genişletilmiş Karar Matrisi

	Min	Min	Mak	Mak	Min	Mak	Mak	Mak	Mak
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**K7**	**K8**	**K9**
W	**0,1186**	**0,1055**	**0,0963**	**0,1143**	**0,1097**	**0,1324**	**0,1018**	**0,1164**	**0,1051**
A1	27,464	3,070	0,826	193932,000	9,300	37700,000	0,460	9,000	0,111
A2	36,976	3,520	0,829	249269,000	13,400	96677,000	0,455	20,000	0,223
A3	3,142	2,131	0,868	24052,000	9,700	7625,000	0,345	11,000	0,182
A4	15,030	4,220	0,880	143851,752	7,300	14343,000	0,522	10,000	0,200
A5	25,710	2,800	0,873	207000,000	6,500	50000,000	0,370	7,000	0,143
Aİ	3,142	2,131	0,880	249269,000	6,500	96677,000	0,522	20,000	0,223
AAİ	36,976	4,220	0,826	24052,000	13,400	7625,000	0,345	7,000	0,111

MARCOS yöntemi ile normalize edilmiş karar matrisi Tablo 16' da gösterilmiştir.

Tablo 16. Normalize Edilmiş Karar Matrisi

	Min	Min	Mak	Mak	Min	Mak	Mak	Mak	Mak
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**K7**	**K8**	**K9**
A1	0,114	1	0,938	0,778	1	0,390	0,881	0,450	0,498
A2	0,085	1	0,942	1,000	0	1,000	0,872	1,000	1,000
A3	1,000	1	0,986	0,096	1	0,079	0,661	0,550	0,815
A4	0,209	1	1,000	0,577	1	0,148	1,000	0,500	0,897
A5	0,122	1	0,993	0,830	1	0,517	0,709	0,350	0,641
Aİ	0,085	0,505	1	1	0,485	1	1	1	1
AAİ	1	1	0,938	0,096	1	0,079	0,661	0,350	0,498

MEREC yönteminden elde edilen kriter ağırlıkları kullanılarak ağırlıklı karar matrisi elde edilir. Tablo 17' de verilmiştir.

Tablo 17. Ağırlıklı Karar Matrisi

	Min	Min	Mak	Mak	Min	Mak	Mak	Mak	Mak
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**K7**	**K8**	**K9**
A1	0,014	0,073	0,090	0,089	0,077	0,052	0,090	0,052	0,052
A2	0,010	0,064	0,091	0,114	0,053	0,132	0,089	0,116	0,105
A3	0,119	0,105	0,095	0,011	0,074	0,010	0,067	0,064	0,086
A4	0,025	0,053	0,096	0,066	0,098	0,020	0,102	0,058	0,094
A5	0,014	0,080	0,095	0,095	0,110	0,068	0,072	0,041	0,067
Aİ	0,010	0,053	0	0	0,053	0	0	0	0
AAİ	0	0	0,090	0,011	0	0,010	0,067	0,041	0,052

Tablo 18 genel performans değerlerini göstermektedir.

Tablo 18. Genel Performans Değerleri

	S_{aai}	S_{ai}
Aİ		0,783
AAİ	0,606	

Fayda fonksiyonları ve hava yolu şirketlerinin performans sıralamaları Tablo 19' da verilmiştir. En iyi performansı A2 alternatifi verirken, A1 alternatifi son sırada kalmıştır.

Tablo 19. Fayda Fonksiyonları ve Sıralama

	S_i	K_i^+	K_i^-	$f(K_i^-)$	$f(K_i^+)$	$f(K_i)$	**Sıralama**
A1	0,589	0,750	0,972	0,564	0,436	2,594	**5**
A2	0,775	0,987	1,279	0,564	0,436	3,004	**1**
A3	0,631	0,804	1,041	0,564	0,436	2,687	**3**
A4	0,612	0,779	1,010	0,564	0,436	2,645	**4**
A5	0,644	0,820	1,062	0,564	0,436	2,715	**2**

5. DUYARLILIK ANALİZİ

Çok kriterli karar verme (ÇKKV) alanında yapılan çalışmalarda kullanılan yöntemlerin bir problem için ne derece uygun olduğunu belirlemeye ya da elde edilen sonuçların güvenilirliğini test etmeye yönelik literatürde ortak bir ölçüt bulunmamaktadır (Demir vd., 2022).

Araştırmalar, özellikle doğru bilginin elde edilmesi sürecindeki hatalar ya da karar vericinin kontrol edemediği belirsizlikler nedeniyle girdi parametrelerinde ortaya çıkabilecek değişimlerin sonuçlar üzerindeki etkisini incelemek amacıyla duyarlılık analizinin kullanılmasını önermektedir. Çözüm sürecinde tercihlerin veya parametre değerlerinin küçük ölçekte değişmesi durumunda yöntemin verdiği sonuçların ne ölçüde sabit kaldığını ya da nasıl davrandığını inceleyen bu yaklaşım, duyarlılık analizi olarak tanımlanmaktadır (Pamučar ve Ćirović, 2017). Duyarlılık analizi, değerlendirilen problemle ilişkili belirsizliği ortaya koymada ÇKKV modelleri için güvenilir bir araç niteliği taşımaktadır. Bu doğrultuda, çalışmanın bulgularının kriter ağırlıklarına duyarlılığını test etmek için duyarlılık analizi yapılmıştır. Entropi ve MEREC yöntemlerine ait duyarlılık analizi sonuçları Tablo 20' de verilmiştir.

Tablo 20. Entropi ve MEREC Yöntemlerine ait Duyarlılık Analizi

	Entropi Yöntemi				MEREC Yöntemi			
	2020	2021	2022	2023	2020	2021	2022	2023
	w_j	w_j	w_j	w_j	w_j	w_j	w_j	w_j
K1	0,140	0,149	0,204	0,223	0,113	0,111	0,118	0,119
K2	0,313	0,208	0,026	0,032	0,281	0,141	0,104	0,105
K3	0,053	0,035	0,003	0,000	0,050	0,098	0,096	0,096
K4	0,208	0,183	0,179	0,194	0,174	0,113	0,116	0,114
K5	0,026	0,042	0,056	0,052	0,060	0,103	0,110	0,110
K6	0,204	0,308	0,417	0,355	0,178	0,147	0,140	0,132
K7	0,010	0,008	0,013	0,015	0,029	0,088	0,099	0,102
K8	0,030	0,044	0,062	0,091	0,074	0,107	0,113	0,116
K9	0,016	0,024	0,039	0,037	0,041	0,092	0,104	0,105

Entropi yöntemi ile MEREC yöntemi arasında bazı kriterlerde belirgin ağırlık farklılıkları olduğu görülmektedir. Özellikle K2, K6 ve K8 kriterlerinde yıllar boyunca iki yöntem arasında dikkate değer sapmalar bulunmaktadır. Entropi yöntemi, veri dağılımındaki belirsizliği esas aldığı için bazı kriterlerde (örneğin K6 ve K2) çok yüksek ağırlıklar üretirken; MEREC yöntemi kriterin modele yaptığı marjinal etkiye odaklandığı için daha dengeli ve daha düşük varyanslı ağırlıklar vermiştir.

K3 ve K7 gibi kriterlerde Entropi ağırlıkları oldukça düşük seyretmesine rağmen MEREC yönteminde bu kriterlerin ağırlıkları yıl bazında daha yüksek ve daha istikrarlı görünmektedir.

Duyarlılık analizi, iki yöntemin aynı karar probleminde farklı hassasiyetlere sahip olduğunu, bu nedenle alternatiflerin sıralamasının yönteme göre değişme potansiyeli bulunduğunu göstermektedir. Bu çeşitlilik, analiz sonuçlarının sağlamasını yapmak ve karar mekanizmasını güçlendirmek açısından yöntemler arası karşılaştırmanın önemli olduğunu ortaya koymaktadır.

5.1. Spearman Korelasyon Analizi

Spearman korelasyon analizi, iki değişken arasındaki ilişkiyi sıralamalar üzerinden inceleyen ve veri dağılımı hakkında herhangi bir varsayım gerektirmeyen nonparametrik bir yöntem olarak tanımlanmaktadır. Bu yaklaşım, değişkenlerin değerlerini büyüklük sırasına göre karşılaştırarak, aralarındaki ilişkinin yönünü ve gücünü ölçer. Özellikle doğrusal olmayan fakat monoton bir ilişki gösteren veri setlerinde güvenilir sonuç verdiği için literatürde sıkça tercih edilmektedir. Bu yöntem ilk kez Spearman (1904) tarafından geliştirilmiş olup, günümüzde sosyal bilimlerden mühendisliğe kadar çok geniş bir alanda kullanılmaktadır (Spearman, 1961). MARCOS ve MABAC yöntemlerinin farklı kriter ağırlıklandırma metotlarına göre sıralamaları Tablo 21' de gösterilmiştir.

Tablo 21. Yöntemlerin Alternatiflere Göre Sıralamaları

	Entropi Tabanlı MARCOS Sıralaması	Entropi Tabanlı MABAC Sıralaması	MEREC Tabanlı MARCOS Sıralaması	MEREC Tabanlı MABAC Sıralaması
A1	3	2,75	4	2,75
A2	1	1	1	1
A3	4	5	2,75	5
A4	5	4	4,25	4
A5	2	2,25	3	2,25

Entropi ve MEREC yöntemlerine ait spearman korelasyon analizi tablosu Tablo 22' de verilmiştir.

Tablo 22. Entropi ve MEREC Yöntemlerine ait Spearman Korelasyon Analizi

	Entropi Tabanlı MARCOS Sıralaması	Entropi Tabanlı MABAC Sıralaması	MEREC Tabanlı MARCOS Sıralaması	MEREC Tabanlı MABAC Sıralaması
Entropi Tabanlı MARCOS Sıralaması	1	0,9	0,8	0,9
Entropi Tabanlı MABAC Sıralaması	0,9	1	0,6	1
MEREC Tabanlı MARCOS Sıralaması	0,8	0,6	1	0,6
MEREC Tabanlı MABAC Sıralaması	0,9	1	0,6	1

Birbirine en yakın sıralamalar 0.9 korelasyon katsayısı ile Entropi Tabanlı MABAC ve Entropi Tabanlı MARCOS ile MEREC Tabanlı MABAC ve Entropi Tabanlı MARCOS yöntemlerinden elde edilen sıralamalar olmuştur.

0.6 korelasyon katsayısı ile MEREC Tabanlı MARCOS ve Entropi Tabanlı MABAC ile MEREC Tabanlı MABAC ve MEREC Tabanlı MARCOS yöntemlerinden elde edilen sıralamaların birbirinden en farklı sıralamalar olduğu görülmüştür.

6. SONUÇLAR VE TARTIŞMA

Lufthansa Airlines, değerlendirilen 4 yıl boyunca hem MABAC hem de MARCOS sonuçlarında tutarlı bir şekilde 1. sırada yer almıştır. Bu durum, şirketin sürdürülebilirlik performansında istikrar sağladığını ve üç ÇSY boyutunda diğer şirketlere göre daha dengeli ve güçlü bir strateji izlediğini göstermektedir.

Qatar Airways, çoğunlukla üst sıralarda yer almış; özellikle 2020, 2021 ve 2023 yıllarında her iki yöntemde de 2. sıradaki güçlü konumunu korumuştur. Ancak 2022 yılında MARCOS'ta 5. sıraya gerilemesi, bu yıl içinde şirketin bazı sürdürülebilirlik göstergelerinde performans kayıpları yaşadığını düşündürmektedir.

Copa Airlines, MARCOS yönteminde 2021 ve 2022'de 2. sıraya kadar yükselmiş olsa da MABAC yöntemi sonuçlarıyla karşılaştırıldığında belirgin bir tutarsızlık görülmüştür. Bu durum, şirketin bazı kriterlerde çok iyi performans gösterirken diğerlerinde geride kaldığını, dolayısıyla dengeli bir ÇSY yapısının henüz oluşmadığını ortaya koymaktadır.

Singapore Airlines, çalışma dönemi boyunca genellikle orta sıralarda yer almış; MABAC sonuçlarında tüm yıllarda 4. sırada sabit kaldığı görülmüştür. MARCOS sonuçlarında ise 2022'de belirgin bir iyileşme ile 3. sıraya yükselmiştir. Bu durum, şirketin özellikle çevresel ve yönetişim kriterlerindeki bazı göstergelerde iyileşme sağladığını göstermektedir.

Türk Hava Yolları (THY), dönem boyunca değişken bir performans sergilemiştir. MARCOS sonuçları 2020'de 3. sırayı işaret ederken, 2023'te şirketin 5. sıraya gerilediği görülmektedir. Bu dalgalanmalı seyir, THY'nin bazı yıllarda özellikle sosyal ve yönetişim göstergelerinde güçlenirken bazı dönemlerde bu alanlarda gerilemeler yaşadığını ortaya koymaktadır.

Tablo 23. Şirketlerin Entropi ve MEREC Tabanlı MARCOS ve MABAC Yöntemlerine ait Sıralamalarının Karşılaştırmalı Tablosu

ÇKKV		ENTROPİ	ENTROPİ	MEREC	MEREC
Hava Yolu	**Yıl**	**MARCOS**	**MABAC**	**MARCOS**	**MABAC**
THY	2020	3	3	3	3
THY	2021	3	3	4	3
THY	2022	3	2	4	2
THY	2023	3	3	5	3
LUFTHANSA	2020	1	1	1	1
LUFTHANSA	2021	1	1	1	1
LUFTHANSA	2022	1	1	1	1
LUFTHANSA	2023	1	1	1	1
COPA	2020	4	5	4	5
COPA	2021	4	5	2	5
COPA	2022	4	5	2	5
COPA	2023	4	5	3	5
SINGAPOR	2020	5	4	5	4
SINGAPOR	2021	5	4	5	4
SINGAPOR	2022	5	4	3	4
SINGAPOR	2023	5	4	4	4
QATAR	2020	2	2	2	2
QATAR	2021	2	2	3	2
QATAR	2022	2	3	5	3
QATAR	2023	2	2	2	2

Genel sonuçlara bakıldığında; Lufthansa tüm yıllarda en sürdürülebilir hava yolu olarak öne çıkmıştır. Qatar Airways güçlü ve istikrarlı bir ikinci sırada yer alırken, Copa ve Singapore orta sıralarda dalgalanarak ilerlemiştir. THY ise özellikle son yılda düşük bir performansla son sıraya düşerek iyileştirme gerektiren alanlara işaret etmiştir.

Bu bulgular, sürdürülebilirlik performans değerlendirmelerinde dengeli ÇSY stratejilerinin önemini açık şekilde göstermektedir. Çalışma, havacılık sektörünün sürdürülebilirlik gelişim dinamiklerini çok boyutlu bir perspektifle ortaya koyarak gelecekteki stratejik planlama süreçleri için kapsamlı bir değerlendirme zemini sağlamaktadır.

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KAZAKİSTAN'IN STEPLERİNDE EKOTURİZM: BURABAY MİLLİ PARKI ÜZERİNE BİR VAKA ÇALIŞMASI

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ÖZET

Bu çalışma, Kazak bozkır ekosisteminin eşsiz bağlamında, olağanüstü doğal güzelliğe sahip bir koruma alanı olan Burabay Milli Parkı'ndaki ekoturizm gelişimini kapsamlı bir şekilde analiz etmektedir. Kazakistan'ın turizm çeşitliliğini artırma çabaları kapsamında, bu araştırma, kırılgan bozkır ortamlarının yönetimine ilişkin zorluklar karşısında ekoturizm ilkelerinin uygulanmasını incelemektedir. Araştırma, mevcut ekoturizm uygulamalarının durumunu değerlendirmek için kapsamlı bir literatür taraması, politika analizi ve saha gözlemlerinden yararlanan nitel bir vaka çalışması metodolojisini benimsemektedir. Analiz, Burabay'ın eşsiz "kayalık orman-bozkır" manzarası, zengin biyolojik çeşitliliği ve yerleşik koruma statüsü ile önemli avantajlara sahip olmasına rağmen, optimal ekoturizm çıktılarını engelleyen birkaç kritik zorluğu ortaya koymaktadır. Bunlar arasında mevsimsel turizm modelleri, yetersiz atık yönetim sistemleri, yetersiz çevresel yorumlama programları ve yerel toplulukların turizm faydalarına anlamlı katılımının sınırlı olması yer almaktadır. Ayrıca, park, potansiyel aşırı yapılaşma ve narin ekosistemleri üzerindeki iklim değişikliği etkilerinden kaynaklanan artan baskılarla karşı karşıyadır. Çalışma, Burabay'ın ekoturizm potansiyelini tam olarak gerçekleştirmesinin çok boyutlu bir strateji gerektirdiği sonucuna varmaktadır. Bu, taşıma kapasitesi değerlendirmelerine dayalı sağlam ziyaretçi yönetim planlarının uygulanmasını, sertifikalı çevre eğitimi ve yorumlama programlarının geliştirilmesini, yerel geçim kaynaklarını iyileştiren topluluk temelli turizm girişimlerinin teşvik edilmesini ve sürdürülebilir finansman mekanizmaları yoluyla koruma önlemlerinin güçlendirilmesini içermektedir. Bulgular, benzer bozkır ekosistemlerinde koruma hedefleri ile sürdürülebilir turizm kalkınmasını dengelemeyi amaçlayan politika yapıcılar ve park yöneticileri için değerli görüşler sunmaktadır.

Anahtar Kelimeler: Ekoturizm, Burabay Milli Parkı, Sürdürülebilir Turizm, Kazakistan, Bozkır Ekosistemi.

ECOTOURISM IN THE STEPPES OF KAZAKHSTAN: A CASE STUDY OF BURABAY NATIONAL PARK

ABSTRACT

This study provides a comprehensive analysis of ecotourism development in Burabay National Park, a protected area of exceptional natural beauty within the unique context of the Kazakh steppe ecosystem. As Kazakhstan seeks to diversify its tourism offerings, this research examines the implementation of ecotourism principles against the challenges of managing fragile steppe environments. The investigation employs a qualitative case study methodology, drawing from extensive literature review, policy analysis, and field observations to assess the current state of ecotourism practices. The analysis reveals that while Burabay possesses significant advantages through its unique "rocky forest-steppe" landscape, rich biodiversity, and established protected status, several critical challenges impede optimal ecotourism outcomes. These include seasonal tourism patterns, inadequate waste management systems, insufficient environmental interpretation programs, and limited meaningful participation of local communities in tourism benefits. Furthermore, the park faces growing pressures from potential overdevelopment and climate change impacts on its delicate ecosystems. The study concludes that realizing Burabay's full ecotourism potential requires a multidimensional strategy. This entails implementing robust visitor management plans based on carrying capacity assessments, developing certified environmental education and interpretation programs, fostering community-based tourism initiatives that enhance local livelihoods, and strengthening conservation measures through sustainable financing mechanisms. The findings offer valuable insights for policymakers and park managers seeking to balance conservation goals with sustainable tourism development in similar steppe ecosystems globally.

Keywords: Ecotourism, Burabay National Park, Sustainable Tourism, Kazakhstan, Steppe Ecosystem.

1. Giriş

Küresel turizm endüstrisi, 21. yüzyılda hızla büyümeye devam ederken, geleneksel kitle turizminin doğal kaynaklar üzerinde yarattığı baskı, biyolojik çeşitlilik kaybı ve kültürel erozyon gibi olumsuz etkiler, sürdürülebilir turizm alternatiflerine olan ilgiyi akademik ve pratik düzeyde artırmıştır (Weaver, 2020). Bu bağlamda ekoturizm, biyolojik çeşitliliğin korunması, yerel halkın refahının artırılması ve çevresel bilincin geliştirilmesi ilkeleri çerçevesinde (Fennell, 2020) öne çıkan bir yaklaşım olarak kabul görmektedir.

Orta Asya bölgesi, Sovyetler Birliği'nin dağılmasından sonra turizm potansiyelini yeniden keşfetmeye başlamıştır. Bölgenin el değmemiş doğal alanları, zengin biyolojik çeşitliliği ve kadim kültürel mirası, ekoturizm için önemli bir potansiyel oluşturmaktadır (Kalipova, 2020). Kazakistan, 2.7 milyon kilometrekarelik yüzölçümüyle bölgenin en büyük ülkesi olup, topraklarının büyük bölümünü oluşturan bozkır (step) ekosistemleri, küresel ölçekte koruma önceliğine sahip biyomlardan biridir (Smithson, 2022).

Bu çalışmanın odağını oluşturan Burabay Milli Parkı ise Kazakistan'ın kuzeyindeki Akmola eyaletinde yer alan ve "Kazakistan'ın İncisi" olarak anılan, 83.511 hektarlık bir korunan alandır. Park, 14 doğal gölü, Paleozoik döneme ait granit kayalıkları ve zengin biyolojik çeşitliliği ile hem ulusal hem de uluslararası düzeyde önem taşımaktadır (Kazakistan Çevre Bakanlığı, 2023).

Bu bildiri, Burabay Milli Parkı özelinde, Kazakistan'ın step ekosistemlerindeki ekoturizm potansiyelini, mevcut durumu ve karşılaşılan zorlukları sürdürülebilirlik perspektifiyle değerlendirmeyi amaçlamaktadır. Çalışma, aşağıdaki araştırma sorularına yanıt aramaktadır:

1. Burabay Milli Parkı'nın mevcut ekoturizm uygulamaları, sürdürülebilir turizm ilkeleriyle ne ölçüde uyumludur?

2. Parkın ekoturizm potansiyelini sınırlandıran temel yönetimsel, çevresel ve sosyo-ekonomik faktörler nelerdir?

3. Bölgede sürdürülebilir bir ekoturizm modeli geliştirmek için hangi stratejik yaklaşımlar benimsenmelidir?

2. Kavramsal Çerçeve ve Literatür

2.1. Sürdürülebilir Turizm ve Ekoturizm

Sürdürülebilir kalkınma kavramı, Brundtland Raporu'nda "gelecek kuşakların kendi ihtiyaçlarını karşılama yeteneğinden ödün vermeden, günümüzün ihtiyaçlarını karşılama" olarak tanımlanmıştır (WCED, 1987, s. 41). Bu paradigmaya dayalı sürdürülebilir turizm, ekonomik kalkınma, çevresel bütünlük ve sosyal eşitlik arasında denge kuran holistik bir yaklaşımdır (Sharpley, 2020).

Ekoturizm ise sürdürülebilir turizmin önemli bir alt dalı olarak, "doğal alanları koruyan, yerel halkın refahını artıran ve ziyaretçilerde çevresel farkındalık yaratan sorumlu seyahat" olarak tanımlanmaktadır (TIES, 2015). Ekoturizmin temel ilkeleri arasında doğal ve kültürel mirasın korunmasına katkıda bulunmak, yerel topluluklara sosyal ve ekonomik faydalar sağlamak, ziyaretçilere çevre eğitimi deneyimleri sunmak ve turizm faaliyetlerinin ekolojik taşıma kapasitesini aşmamasını sağlamak yer alır (Honey, 2018).

2.2. Korunan Alanlarda Ekoturizm ve Step Ekosistemlerinin Önemi

Korunan alanlar, ekoturizm uygulamaları için ideal mekanlar olarak kabul edilmektedir. Bu alanlarda ekoturizm, hem koruma çalışmaları için alternatif finansal kaynak yaratmakta hem

de yerel halkta ve ziyaretçilerde koruma bilincinin gelişmesine katkı sağlamaktadır (Eagles, 2021). Step ekosistemleri ise dünya karasal biyomlarının %8'ini oluşturmasına rağmen, koruma statüsü açısından en az korunan biyomlar arasında yer almaktadır (UNEP, 2022). Bu nedenle, step ekosistemlerindeki korunan alanlarda uygulanacak sürdürülebilir ekoturizm modelleri, küresel biyolojik çeşitliliğin korunması açısından hayati öneme sahiptir.

3. Araştırmanın Amacı, Kapsamı ve Yöntemi

Bu araştırma, nitel araştırma paradigmasına uygun olarak vaka çalışması deseninde tasarlanmıştır. Vaka çalışması deseni, karmaşık sosyal olguların derinlemesine incelenmesine olanak tanıması nedeniyle bu araştırma için uygun bulunmuştur (Yin, 2018). Burabay Milli Parkı, step ekosisteminde ekoturizm uygulamalarının tipik bir örneği olarak ele alınmıştır.

Araştırmada aşağıdaki veri toplama teknikleri kullanılmıştır: Çalışma, 2020-2023 dönemini kapsamakta olup, Burabay Milli Parkı ile sınırlandırılmıştır.

- **İkincil Veri Analizi:** Akademik yayınlar, resmi istatistikler, kurum raporları ve politika belgelerinin sistematik analizi.
- **Doküman Analizi:** Park yönetim planları, strateji dokümanları ve çevresel izleme raporlarının incelenmesi.

4. Bulgular: Burabay Milli Parkı'nda Mevcut Durum ve Ekoturizm Faaliyetleri

4.1. Fiziko-Coğrafik ve Ekolojik Özellikler

Burabay Milli Parkı, Kazakistan'ın coğrafi olarak "Kazakistan Granit Platosu" üzerinde yer almaktadır. Bu plato, Paleozoik döneme ait granit kayalıkları ve 14 adet doğal gölden oluşan jeolojik açıdan benzersiz bir yapı sergilemektedir (Petrov & Ivanova, 2022). Parkın jeolojik yapısı, 300-350 milyon yıl öncesine dayanan magmatik kayaçlardan oluşmakta olup, bölgedeki en yüksek nokta 947 metre yüksekliğindeki Kokşetau Dağı'dır.



Şekil 1. Burabay Milli Parkı uydu görüntüsü (Google earth 2025).

Burabay Milli Parkı'nın Temel Fiziko-Coğrafik Özellikleri Tablo 1'de gösterilmiştir.

Tablo 1: Burabay Milli Parkı'nın Temel Fiziko-Coğrafik Özellikleri (Burabay Milli Parkı Yönetim Planı, 2023).

Parametre	Değer	Açıklama
Yüzölçümü	83.511 hektar	Toplam korunan alan
Rakım	300-947 metre	Deniz seviyesinden yükseklik
Ana Göl Sayısı	14	Doğal tatlısu gölleri
Toplam Göl Yüzeyi	6.850 hektar	Park alanının %8.2'si
Ormanlık Alan	45.200 hektar	Park alanının %54.1'i
Jeolojik Yaş	300-350 milyon yıl	Paleozoik dönem

Parkın florası, step ve orman-step geçiş zonunun karakteristik özelliklerini yansıtmaktadır. 657 damarlı bitki türü tespit edilmiş olup, bunların 45'i endemik, 28'i ise nadir ve tehlike altındaki türler kategorisinde yer almaktadır (Kazakistan Botanik Enstitüsü, 2023). Fauna ise 54 memeli türü ve 238 kuş türüyle temsil edilmektedir. Burabay Milli Parkı'nın florası Şekil 2'de gösterilmiştir.



Şekil 2. Burabay Milli Parkı'nın florası (URL 2),

Burabay Milli Parkı, olağanüstü zengin bir biyolojik çeşitliliğe sahiptir. Park sınırları içinde **757 bitki türü** tespit edilmiştir; bunlardan **119'u koruma altında** olup, **12'si Kırmızı Kitap'ta** kayıtlıdır. Orman örtüsünün yaklaşık **%65'ini çamlar**, **%31'ini huş ağaçları**, **%3'ünü titrek kavaklar** oluştururken, kalan **%1'lik kesim çalılıklar** ile kaplıdır. Bu zengin bitki örtüsü, bölgede çok sayıda **yenilebilir mantar türünün** yetişmesine de olanak sağlamaktadır.

Bitkisel çeşitlilik, doğal olarak parkın **faunasını da oldukça zenginleştirmiştir.** Burabay'da, Kazakistan genelinde görülen hayvan türlerinin **%36'sını temsil eden 305 farklı tür** yaşamaktadır. Bu türlerin **yaklaşık %40'ı yaşam alanlarının sınırında** bulunurken, **13 tür Kırmızı Kitap'ta** koruma altına alınmıştır. Step ekosistemindeki biyolojik çeşitlilik bileşenleri Şekil 3'te gösterilmiştir.



Şekil 3. step ekosistemindeki biyolojik çeşitlilik bileşenleri (URL 1).

Burabay'ın **vahşi yaşamı**, çevresini saran bozkır alanlarına göre çok daha zengindir. Burada **bozkır, orman ve dağ ekosistemlerine ait türler** bir arada varlık göstermektedir. Parkta yalnızca **Avrupa kökenli türler** değil; aynı zamanda **Sibirya, Kuzey ve Güney bölgelerine özgü hayvan türleri** de gözlemlenebilir.

Orman ekosisteminde **karaca, geyik, yaban domuzu, sincap, kakım, çakal, sansar** ve çeşitli **geyik türleri** yaşamaktadır. **Kurt** ve **vaşak** gibi yırtıcı türlerle de karşılaşmak mümkündür. Bozkır ve orman geçiş alanlarında ise **porsuk, tilki, gelincik, Avrupa tavşanı** ve **dağ tavşanı** gibi memeliler sıklıkla görülür. Sıklıkla görülen yabani hayvan türleri şekil 4'te gösterilmiştir.



Şekil 4. bozkurt, karaca, yaban domuzu ve step tilkisi (URL 8).

Parkın kuş çeşitliliği de dikkat çekicidir. Burada **bayağı altıngöz, yaban ördeği, boz ördek, kılkuyruk, al yanaklı angut, yağmur kuşu, kuzey kız kuşu, dere düdükçünü** ve **yeşil düdükçün** gibi birçok kuş türü kaydedilmiştir. Özellikle **sonbahar ve göç dönemlerinde** ördek popülasyonunda belirgin bir artış gözlemlenir.

Kuru taşlı çam ormanlarında ve **huş bozkırlarının** arasında, **gri keklik** ve **büyük orman tavuğu** gibi kuş türlerine de rastlanmaktadır. Tüm bu unsurlar bir arada değerlendirildiğinde, Burabay Milli Parkı'nın **hem flora hem de fauna açısından Orta Asya'nın en önemli doğal zenginlik alanlarından biri** olduğu söylenebilir

4.2. Mevcut Ekoturizm Aktiviteleri ve Ziyaretçi Profili

Burabay Milli Parkı'nda ekoturizm faaliyetleri, sürdürülebilir turizm prensipleri çerçevesinde yapılandırılmıştır. 2023 yılı verilerine göre parkı yıllık ortalama 285.000 ziyaretçi ağırlamakta olup, bu ziyaretçilerin %65'i yerli turistlerden, %35'i ise uluslararası turistlerden oluşmaktadır (Burabay Milli Parkı Yönetimi, 2024). Şekil 5'te korunan alanlarda uygulanan ekoturizm aktivitelerinden geleneksel göçebe kültürü deneyimine bir örnek gösterilmiştir.



Şekil 5. korunan alanlarda uygulanan ekoturizm aktivitelerinden geleneksel göçebe kültürü deneyimi (URL 5).

Park bünyesindeki başlıca ekoturizm aktiviteleri şunlardır:

- **Doğa Yürüyüşü (Trekking):** Toplam 85 km uzunluğunda işaretlenmiş 12 farklı parkur.
- **Bisiklet Turları:** 45 kilometrelik bisiklet parkuru ağı ve elektrikli bisiklet kiralama sistemi.
- **Kuş ve Yaban Hayatı Gözlemciliği:** 12 adet kuş gözlem kulesi ve 8 adet kamufle edilmiş gözlem noktası.
- **Çevre Eğitimi Programları:** İnteraktif doğa sergileri, rehberli turlar ve atölye çalışmaları.

4.3. Turizmin Çevresel ve Sosyo-Ekonomik Etkileri

Çevresel Etkiler: Yoğun ziyaretçi kullanımına bağlı olarak, özellikle yaz aylarında çöp birikimi önemli bir sorun teşkil etmektedir. 2023 yılında park alanından toplanan katı atık miktarı 85 ton olarak kaydedilmiştir (Waste Management Report, 2024). Erozyon riski özellikle yoğun kullanılan yürüyüş parkurlarında gözlemlenmekte olup, toplam parkur ağının %15'inde orta ve yüksek seviyede erozyon riski tespit edilmiştir.

Sosyo-Ekonomik Etkiler: Ekoturizm faaliyetleri, bölge halkı için önemli bir istihdam kaynağı oluşturmaktadır. Parkın doğrudan istihdam ettiği 125 personelin %70'i yerel halktan oluşmaktadır (Burabay Employment Statistics, 2024). Dolaylı istihdam ise konaklama, yiyecek-içecek ve rehberlik hizmetleri gibi alanlarda 450 kişiye iş imkanı sağlamaktadır. Ancak, yerel halkın turizm karar alma süreçlerine katılım oranı %35 olarak ölçülmüş olup, bu oranın artırılması yönünde beklentiler bulunmaktadır (Community Perception Survey, 2024).

5. Tartışma: SWOT Analizi ve Temel Zorluklar

Burabay Milli Parkı'nın mevcut durumuna ilişkin yapılan analizler, aşağıdaki SWOT matrisini ortaya koymaktadır:

Güçlü Yönler (Strengths):

- Benzersiz jeolojik oluşumlar ve 14 doğal gölden oluşan olağanüstü peyzaj çeşitliliği
- Zengin biyolojik çeşitlilik (657 bitki, 238 kuş türü)
- Gelişmiş altyapı (85 km parkur, 12 gözlem kulesi)
- Astana'ya yakın konum (250 km) ile ulaşılabilirlik

Zayıf Yönler (Weaknesses):

- Belirgin mevsimsel turizm yoğunluğu (Ziyaretçilerin %75'i yaz aylarında)
- Profesyonel rehberlik hizmetlerinin ve dil çeşitliliğinin yetersizliği
- Yerel halkın karar alma süreçlerine düşük katılımı (%35)
- Atık yönetimi ve erozyon kontrolünde yaşanan sorunlar

Fırsatlar (Opportunities):

- Küresel ekoturizm pazarının büyümesi (2023'te 365 milyar ABD Doları)
- Dijital teknolojilerin gelişimi (akıllı turizm uygulamaları)
- Kazakistan'ın vize kolaylaştırma politikaları
- "Orta Asya Yeşil Yolu" gibi bölgesel işbirlikleri

Tehditler (Threats):

- İklim değişikliğinin ekosistemler üzerindeki olumsuz etkileri
- Kaçak yapılaşma ve plansız turizm gelişimi
- Artan ziyaretçi sayısına bağlı habitat parçalanması riski
- Finansman yetersizliği ve kırsal göç

6. Sonuç ve Stratejik Öneriler

Bu çalışma, Burabay Milli Parkı'nın önemli bir ekoturizm potansiyeline sahip olmasına rağmen, bu potansiyeli gerçekleştirmek önünde çok boyutlu zorluklarla karşı karşıya olduğunu ortaya koymuştur. Mevsimsellik, altyapı yetersizlikleri, yerel katılımın sınırlılığı ve iklim değişikliği, parkın sürdürülebilir yönetimini tehdit eden başlıca faktörlerdir.

Burabay Milli Parkı'nda sürdürülebilir bir ekoturizm modeli geliştirilmesi için aşağıdaki stratejik öneriler sunulmaktadır:

6.1. Yönetim ve Planlama Önerileri

- **Akıllı Turizm Yönetim Sistemi:** Gerçek zamanlı ziyaretçi takip sistemi, çevresel izleme sensörleri ve dijital rezervasyon platformu entegrasyonu.
- **Dinamik Taşıma Kapasitesi Modeli:** Ziyaretçi yoğunluğunun anlık olarak yönetilmesi ve mevsimselliğin azaltılması.
- **Katılımcı Yönetim Modeli:** Yerel halkın karar alma süreçlerine katılım oranının %35'ten en az %60'a çıkarılması.

6.2. Çevresel Sürdürülebilirlik Önerileri

- **Ekosistem Tabanlı Adaptasyon:** İklim değişikliğine dayanıklı türlerin korunması ve habitat koridorlarının oluşturulması.
- **Sıfır Atık Hedefi:** Atık yönetim sisteminin modernizasyonu ve döngüsel ekonomi prensiplerinin uygulanması.
- **Yenilenebilir Enerji Geçişi:** 2028 yılına kadar parkın enerji ihtiyacının %80'inin yenilenebilir kaynaklardan karşılanması.

6.3. Sosyo-Ekonomik Sürdürülebilirlik Önerileri

- **Kapsayıcı İş Modelleri:** Yerel halkın turizm gelirlerinden adil pay almasını sağlayacak kooperatif sistemlerinin kurulması.
- **Gelir Çeşitlendirme:** Düşük sezon turizmini teşvik edecek programların geliştirilmesi (kış turizmi, kültür turizmi).
- **Kapasite Geliştirme:** Yerel halkın turizm sektöründe nitelikli istihdamını artırmak için mesleki eğitim programları.

6.4. Eğitim ve Farkındalık Önerileri

- **Kapsamlı Eğitim Programı:** Ziyaretçiler, yerel halk ve personel için sürdürülebilir turizm eğitimlerinin düzenlenmesi.
- **Dijital İletişim Stratejisi:** Sosyal medya ve dijital platformların etkin kullanımı ve sanal gerçeklik deneyimleri.
- **Bilimsel İşbirlikleri:** Üniversitelerle ortak araştırma ve izleme programlarının geliştirilmesi.

Sonuç olarak, Burabay Milli Parkı'nın sürdürülebilir geleceği, koruma ve kullanma dengesinin bilimsel temellere dayalı, katılımcı ve uyumlu bir yönetim anlayışıyla sağlanmasına bağlıdır. Bu çalışmanın bulguları ve önerileri, benzer step ekosistemlerindeki korunan alanlar için bir yönetim çerçevesi sunma potansiyeli taşımaktadır.

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PARALLEL SINGLE SEEKERS SOCIETY ALGORITHM INCORPORATED MACHINE LEARNING FOR SOLVING CONTINUOUS OPTIMIZATION PROBLEMS

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ABSTRACT

Optimization problems have long been addressed using a variety of metaheuristic approaches, each offering distinct strengths and weaknesses. According to the No Free Lunch Theorem, no single metaheuristic algorithm can outperform all others across a broad range of optimization problems. Therefore, employing different metaheuristics within an adaptive framework can be an effective way to improve search performance. This study introduces a parallelized version of the Single Seekers Society (PSSS) Algorithm, an effort to enhance computational efficiency and performance in complex optimization problems. The original Single Seekers Society (SSS) combines several single-solution metaheuristics, such as Simulated Annealing, Greedy Search, Great Deluge, and Threshold Accepting, under the coordination of a population-based metaheuristic such as Genetic Algorithm, Differential Evolution. In PSSS, all single-solution metaheuristics operate on solutions simultaneously rather than sequentially, to speed up the search process. In the improved version proposed in this study, a bandit approach is incorporated into the PSSS framework to enable adaptive selection of single-solution metaheuristic based on performance feedback**.** The bandit-based mechanism dynamically adjusts the selection probabilities of metaheuristics depending on their recent success, allowing the algorithm to learn which strategies perform better for the given search landscape. This adaptive process strengthens the balance between exploration and exploitation while preserving diversity. The proposed PSSS algorithm was evaluated on the CEC 2022 benchmark suite, which includes highly complex optimization problems. Experimental findings indicate that the bandit incorporated PSSS achieves competitive performance in comparison to the reported results in the literature. Moreover, parallel execution of SSS significantly reduced computational time while preserving solution quality.

Keywords: Single Seekers Society, Parallel Programming, Metaheuristic Algorithms, Continuous Optimization, Bandit Approach

1. Introduction

Optimization problems arise in various scientific and engineering applications, including parameter estimation (Zhang et al., 2024), scheduling (Dauzère-Pérès et al., 2024), clustering (Jia et al., 2024), and control problems. When the problem becomes more complex, especially in high-dimensional, nonlinear, and multimodal cases, then classical mathematical programming approaches become either inadequate or computationally expensive. This scenario has made approximation-based approaches popular, particularly metaheuristic algorithms, which provide a balance between exploration and exploitation without the need for gradient information or stringent structural assumptions (Blum and Roli, 2003).

Metaheuristics encompass a broad range of general search strategies inspired by natural, physical, or logical phenomena. While many effective methods have been developed, their performance often varies significantly across different problem categories. The No Free Lunch Theorem illustrates this by showing that no single optimization algorithm outperforms all others across every possible class of problems (Wolpert and Macready, 1997). This understanding has led to increased focus on hybrid designs, adaptive frameworks, and parallel architectures in research, as each aims to combine the complementary strengths of various search operators.

In this regard, Single Seekers Society (SSS) is a coalition-based metaheuristic framework proposed by Baykasoğlu et al. (2019) that combines various single-solution based metaheuristic methods under one umbrella. Instead of conducting a search based on a single trajectory, SSS runs multiple single-solution metaheuristics, including Simulated Annealing, Great Deluge, Greedy Search, and Threshold Accepting etc., in a coordinated manner. Each metaheuristic independently explores the solution space using its own neighborhood structure, while information-sharing mechanisms oversee the overall convergence process. SSS is neither a hybrid nor a hyper-heuristic; it is a coalition-based metaheuristic framework in which different search behaviors work together within a unified structure. Later extensions demonstrated that this framework could be applied not only to continuous optimization but also to combinatorial problems (Hamzadayı et al., 2020), demonstrating its versatility.

The original SSS framework claims high conceptual richness but operates sequentially; the single-solution metaheuristics update their states one after another, which can limit scalability and increase computational costs for demanding benchmark problems. Additionally, the selection of a single-solution metaheuristic is random; therefore, SSS does not adaptively focus more on successful strategies during the run. These factors make SSS an intriguing candidate for further improvements in parallelization and learning-based adaptation.

This paper explores a parallel version of the SSS framework and an adaptive bandit-based metaheuristic selection strategy. All single-solution-based metaheuristics are executed simultaneously to leverage multicore architectures, thereby decreasing the total runtime. Additionally, a bandit-based approach dynamically updates the selection probabilities of the metaheuristics based on their recent performance, enabling the algorithm to favor more promising search strategies while preserving diversity. This design transforms the SSS framework into a more adaptive and data-driven system that can modify its search dynamics according to the characteristics of the problem landscape.

To evaluate the effectiveness of the new Parallel Single Seekers Society (PSSS) algorithm, we conducted computational tests using the CEC 2022 benchmark suite, which includes challenging problems for continuous optimization with various types of functions like unimodal, hybrid, and composition. We assessed performance by examining the

quality of solutions and the speed at which they were discovered. The results indicated that PSSS performed as well as some well-known metaheuristics but required significantly less time due to its use of parallel and bandit enhancements. Thus, this study makes three main contributions: implementing a parallelized SSS framework, developing an adaptive bandit-based mechanism for selecting metaheuristics, and conducting extensive empirical analysis on the CEC 2022 test functions.

The rest of the paper is organized as follows: Section 2 describes the main components of our proposed algorithm. Section 3 provides detailed information on the experimental setup and analysis conducted in this study. Finally, Section 4 concludes with potential future research directions.

2. Methodology

The methodological background of the study and the extension of the original SSS algorithm are presented in this section. Since the proposed enhancements directly build upon the original structure of the SSS, it is first useful to revisit how the algorithm operates in its baseline form.

2.1. Overview of the SSS algorithm

The SSS algorithm is a coalition-based framework that coordinates multiple single-solution-based metaheuristics and models both individual and collective behavioral patterns in a social context (Baykasoğlu et al., 2019). Instead of following traditional hybrid or hyper-heuristic systems, SSS centers its approach around a more unique idea: it brings together several single-solution heuristics under one umbrella and considers them members of a small "society". Each member maintains its own identity but still interacts with others through a shared population-based structure. In this way, SSS functions less as a standalone algorithm and more as a coordinated collection of search behaviors.

The SSS framework can be better understood by examining four conceptual layers. First, the framework itself represents a social behavior model that defines how individuals may act and how information may circulate within the group. Second, family characteristics relate to the type of single-solution metaheuristic assigned to each individual, similar to inheriting a behavioral tendency from one's family. Third, personal characteristics reflect the parameter set of the assigned heuristic, giving each individual their own unique style even when sharing the same heuristic type with others. Finally, social interaction involves crossover, where individuals exchange information, much like community members influence or shape each other's decisions.

The algorithm begins with initializing the population. Each individual in the population is assigned a single-solution-based metaheuristic, such as Simulated Annealing, Threshold Accepting, Great Deluge, or Greedy Search. This assignment determines the "family" to which the individual belongs. Then, parameter values are drawn from predefined intervals that have been discretized into subranges; one subrange is chosen at random, and a continuous value is drawn from within it. Due to this two-step sampling process, individuals can behave very differently even if they share the same heuristic type.

With these initialization conditions in place, individuals start their own search processes. Each individual "grows" by executing its assigned metaheuristic until it reaches what can be considered maturity. After this stage, individuals participate in a reproduction process driven by a population-based metaheuristic algorithm, such as Genetic Algorithm (GA) or Differential Evolution (DE). Through crossover and occasional mutations, individuals share information

and generate new candidate solutions, while elitism ensures that the best-performing individuals are preserved in the pool.

To better visualize how these steps occur within the algorithm, an overall workflow of SSS is summarized in Figure 1.

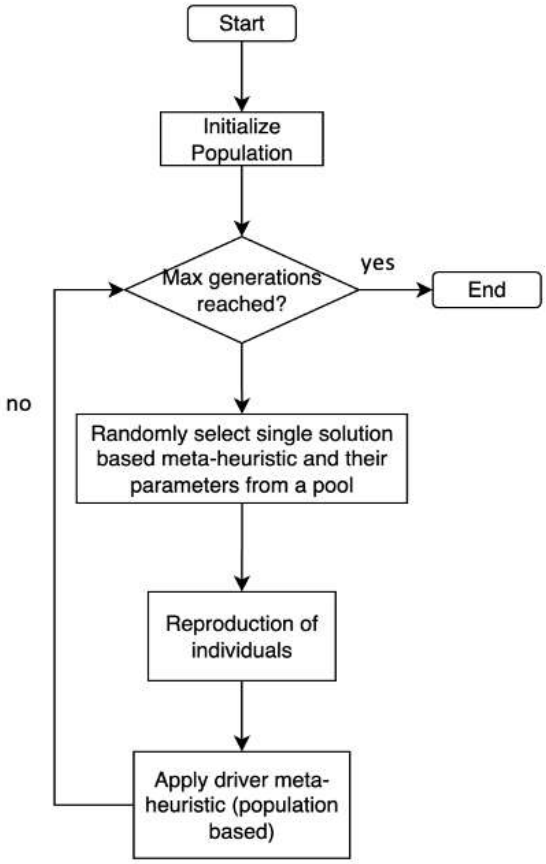

Figure 1: Simplified flow chart of the SSS algorithm

2.2. Motivations for extending the SSS algorithm

The SSS is an algorithm with a flexible structure that allows multiple single-solution-based search algorithms to coexist and interact. Because of this flexibility, it can serve as a solid foundation for methodological extensions. During our preliminary experiments, we identified certain steps in the original SSS workflow where targeted modifications could improve the algorithm's performance. These modifications speed up the process and enhance solution quality by altering how individual heuristics are selected and how the single-solution search phase is executed. These insights inspired the extensions presented in this study, which focus on two complementary areas: enabling parallel execution within the Single Seeker stage and implementing an adaptive, learning-driven mechanism for heuristic selection.

Building on these observations, we proposed two extensions that naturally integrate into the SSS framework: (i) parallelization of the Single Seeker stage to remove unnecessary sequential dependencies, and (ii) incorporating a multi-armed bandit framework to adaptively choose heuristics during the search. These changes enhance SSS's efficiency, speed, and awareness of the problem being addressed.

2.3. Parallelization of the reproduction part of the SSS algorithm

In the original SSS framework, all individuals execute their respective single-solution metaheuristics sequentially. This sequential approach keeps the framework simple, but it results in a significant amount of idle time since individuals do not depend on each other's intermediate results. Therefore, it can be executed in parallel without any benefit from running sequentially. During our experiments, it was observed that these independent search processes are ideally suited for parallel execution, especially since modern computational environments are mostly multi-threaded. To leverage this independence, the first extension proposed in this work modifies the reproduction phase by allowing all individuals to simultaneously perform their assigned single-solution-based metaheuristics. This change does not alter the core principles of the SSS framework, as each individual still conducts its search independently; however, it enables the population to reach the reproduction phase much faster. As demonstrated by the experimental results, this restructuring yields a significant improvement in runtime performance while maintaining solution quality.

2.4. Single-solution-based metaheuristic selection via Multi-Armed Bandit learning

The second extension introduced in this study aims to make the selection of single-solution-based metaheuristics smarter rather than random. In the original SSS framework, heuristics were assigned to individuals without bias and uniformly, which maintained diversity but lacked a mechanism to favor heuristics that performed better during search. To overcome this limitation, we integrated a learning-based approach using the Multi-Armed Bandit (MAB) method.

In this setup, each single-solution-based metaheuristic is viewed as an “arm" of the bandit. During optimization, the algorithm monitors the contribution of each heuristic to improving the objective function and uses this information to update its preferences. The aim is to balance two behaviors: exploration, which involves occasionally trying all heuristics to prevent premature convergence, and exploitation, which encourages the algorithm to focus on heuristics that have recently yielded more significant improvements. The learning mechanism adheres to the classical bandit principles described in Slivkins (2019).

Let H=$\{h_1,\ldots, h_k\}$denote the set of available single-solution-based metaheuristics. For each heuristic h_k the algorithm maintains a value estimate $Q_k$which represents its expected contribution to solution improvement. After each generation, these estimates are updated by using the observed fitness differences from individuals that used the corresponding single-solution-based metaheuristics.

For minimization problems, the improvement generated by individual i is quantified as

$\Delta_i = f_{old(i)} - f_{new(i)}$,

Where a positive value designates a successful improvement. For each heuristic h_k , let S_k denote the set of individuals that applied it in the current generation. If at least one improvement is observed, the reward for that heuristic is computed as

$r_k = \frac{1}{|S_k|}\sum_{i \in S_k} \Delta_i$,

The value estimates are then updated through a standard exponential smoothing rule:

$Q_k \leftarrow (1-\alpha)Q_k + \alpha\, r_k$,

where $\alpha \in (0,1)$ is the learning rate. A decreasing exploration rate, denoted by ε, determines whether the heuristic for each new individual is chosen uniformly or based on the largest current estimate, Q_k. After each generation, ε is gradually reduced.

The adaptive selection procedure used in this study is formalized in Algorithm 1, which incorporates a multi-armed bandit learning mechanism into the PSSS framework.

Algorithm 1: Bandit-based heuristic selection in the PSSS framework

Input : set of single-solution metaheuristics $H = \{h_1, \ldots, h_K\}$;
parameter sets of these metaheuristics;
parameters of the population-based driver;
bandit parameters α, $\varepsilon_{start}, \varepsilon_{\min}, \varepsilon_{decay}$

Output: updated value estimates Q_k and exploration rate ε

Initialisation:

`// initial population generation`

P(i,:) = LL + rand(NP,D) (UL-LL), i=1,...,NP

foreach $h_k \in H$ **do**
  $Q_k \leftarrow 0$

$\varepsilon \leftarrow \varepsilon_{start}$

Main loop:

foreach *generation* $t = 1, 2, \ldots$ **do**

  `// heuristic assignment for the current generation`

  foreach *individual* i *in the population* **do**
    if *random()* $< \varepsilon$ **then**
      choose h_k uniformly from H
    else
      choose $h_k = \arg\max_{h_j \in H} Q_j$
    assign h_k to individual i

  `// parallel execution of Single Seekers`

  run all assigned single solution based metaheuristic **concurrently** on the individuals, each producing an updated objective value $f_{new}(i)$

  `// reward computation and value update`

  foreach $h_k \in H$ **do**
    collect all improvements $\Delta_i = f_{old}(i) - f_{new}(i)$ from individuals that used h_k in generation t
    if *at least one* Δ_i *is available* **then**
      let r_k be the average of these improvements
      $Q_k \leftarrow (1-\alpha)\, Q_k + \alpha\, r_k$

  `// exploration rate update`

  $\varepsilon \leftarrow \max(\varepsilon_{\min}, \varepsilon \cdot \varepsilon_{decay})$

3. Experimental results

In this study, the proposed PSSS framework is tested with two different population-based driver heuristics: GA and DE. All variants were combined with the same set of single-solution-based metaheuristics, including the random selection baseline. In the bandit-enhanced versions, the multi-armed bandit mechanism dynamically selected the most promising heuristic for each individual during the optimization process. The performance of the proposed PSSS variants was assessed on the CEC 2022 benchmark suite, which features 12 challenging test functions from different categories, unimodal, basic, hybrid, and composition. Although the suite contains 12 functions, our analysis focuses on the first seven functions (F1–F7), as these are the ones for which complete experimental results were generated under the 10-dimensional setting. A summary of the benchmark definitions is provided in Table 1.

Table 1: Benchmark functions for the performance evaluation of PSSS

No	Name	Class	Range	f_{min}
F1	Shifted and full rotated Zakharov function	Unimodal functions	[-100,100]	300
F2	Shifted and full Rosenbrock's function	Basic functions	[-100,100]	400
F3	Shifted and full rotated expanded Scaffer's F6 function			600
F4	Shifted and full rotated non-continuous Rastrigin's function			800
F5	Shifted and rotated Levy function			900
F6	Hybrid function 1 (N = 3)	Hybrid functions	[-100,100]	1800
F7	Hybrid function 2 (N = 6)			2000

The first batch of results examines how computational work is affected when we attempt to reproduce using parallel computing. Figure 2 shows the average time taken by PSSS-GA (Serial) and PSSS-GA (Parallel) for F1–F7, measured in seconds. Running it in parallel reduces the time needed to execute each function, especially where there is a lot of math involved, like in F4, F6, and F7. The difference becomes more evident as the complexity increases, supporting the idea that more complex tasks require more time for each reproduction part.

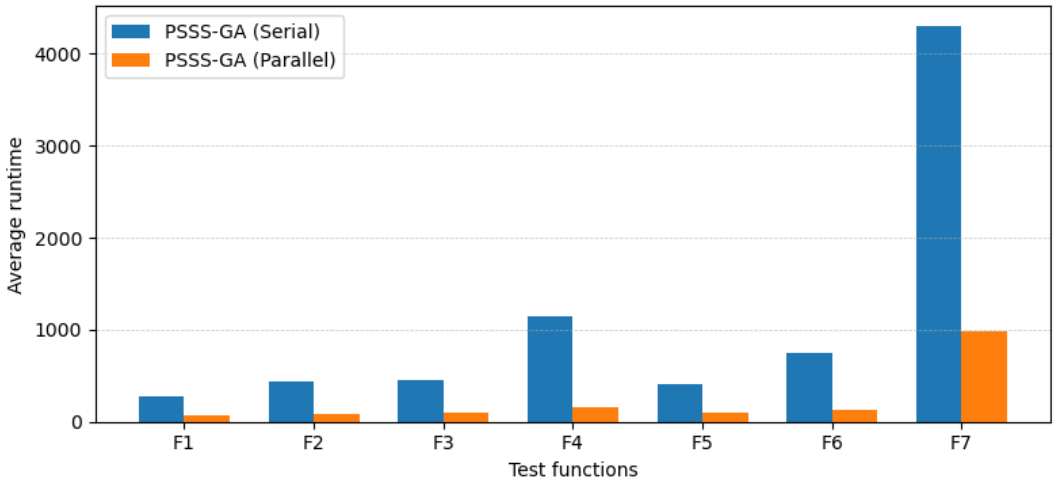

Figure 2: Average runtime comparison of serial and parallel PSSS implementations

To evaluate the impact of adaptive single-solution-based metaheuristic selection, we compared four variants of the PSSS framework: two baseline configurations, PSSS-GA and PSSS-DE, which relied on random assignment of single-solution-based metaheuristics, and two enhanced configurations, PSSS-GA (Bandit) and PSSS-DE (Bandit), which integrated the multi-armed bandit mechanism for dynamically selecting the most promising operator. This setup enabled us to isolate the contribution of the bandit component independently of the population-based driver.

Table 2: The comparison results of PSSS and versions for CEC 2022 test functions

F	Metric	PSSS_GA	PSSS_DE	PSSS_GA(Bandit)	PSSS_DE(Bandit)
F1	Best	**300.00**	**300.00**	**300.00**	**300.00**
F1	Mean	**300.00**	**300.00**	**300.00**	**300.00**
F1	Median	**300.00**	**300.00**	**300.00**	**300.00**
F1	StdDev	3.14×10^{-5}	3.21×10^{-5}	3.45×10^{-6}	**1.10×10^{-7}**
F1	Worst	**300.00**	**300.00**	**300.00**	**300.00**
F2	Best	**400.00**	**400.00**	**400.00**	**400.00**
F2	Mean	**400.00**	**400.00**	**400.00**	**400.00**
F2	Median	**400.00**	**400.00**	**400.00**	**400.00**
F2	StdDev	1.46×10^{-3}	8.28×10^{-3}	**9.80×10^{-5}**	1.30×10^{-4}
F2	Worst	**400.00**	400.04	**400.00**	**400.00**
F3	Best	**600.00**	**600.00**	**600.00**	**600.00**
F3	Mean	**600.00**	**600.00**	**600.00**	**600.00**
F3	Median	**600.00**	**600.00**	**600.00**	**600.00**
F3	StdDev	1.43×10^{-9}	1.12×10^{-9}	9.26×10^{-11}	**3.14×10^{-12}**
F3	Worst	**600.00**	**600.00**	**600.00**	**600.00**
F4	Best	**808.01**	808.36	812.00	816.00
F4	Mean	818.26	**816.73**	820.20	825.01
F4	Median	817.48	**816.01**	820.00	826.00
F4	StdDev	7.43	**4.79**	5.44	4.87
F4	Worst	836.00	**826.44**	832.00	836.00
F5	Best	**900.00**	**900.00**	**900.00**	**900.00**
F5	Mean	**900.00**	**900.00**	900.12	900.09
F5	Median	**900.00**	**900.00**	**900.00**	**900.00**
F5	StdDev	1.25×10^{-3}	**4.57×10^{-7}**	0.39	0.38
F5	Worst	900.01	**900.00**	901.73	901.73
F6	Best	1.81×10^{3}	1.90×10^{3}	**1.80×10^{3}**	1.81×10^{3}
F6	Mean	2.68×10^{3}	2.41×10^{3}	1.93×10^{3}	**1.89×10^{3}**
F6	Median	2.27×10^{3}	2.37×10^{3}	**1.88×10^{3}**	1.89×10^{3}
F6	StdDev	8.12×10^{2}	4.50×10^{2}	1.33×10^{2}	**6.41×10^{1}**
F6	Worst	4.94×10^{3}	3.74×10^{3}	2.36×10^{3}	**2.03×10^{3}**
F7	Best	2.00×10^{3}	2.00×10^{3}	2.00×10^{3}	2.00×10^{3}
F7	Mean	2.00×10^{3}	2.00×10^{3}	2.00×10^{3}	2.00×10^{3}
F7	Median	2.00×10^{3}	2.00×10^{3}	2.00×10^{3}	2.00×10^{3}
F7	StdDev	0.37	0.58	0.03	0.09
F7	Worst	2.00×10^{3}	2.00×10^{3}	2.00×10^{3}	2.00×10^{3}

As shown in Table 2, all variants perform well on the first three benchmark functions (F1–F3), with only small differences between single-solution-based metaheuristic-selection strategies. The divergence between methods becomes more apparent from F4 onward, especially for the hybrid functions F6 and F7, where the search space is more irregular, making the algorithms more challenging to solve.

A review of the results indicates that PSSS-GA (Bandit) is the most consistent performer, achieving the best results on six out of seven tested functions. This suggests that the bandit mechanism is particularly effective when used with the GA driver. Generally, this bandit-guided selection process results in a more stable generational progression and better solution quality for most functions.

Figure 3's radar chart compares the PSSS model with several classic metaheuristics reported in the literature (Chen et al., 2023). Each polygon illustrates how well an algorithm performs relative to others across all CEC 2022 test functions; smaller enclosed areas indicate better overall results. In seven tested functions (F1–F7), traditional population-based methods such as Particle Swarm Optimization (PSO) (Kennedy and Eberhart, 1995), Whale Optimization Algorithm (WOA) (Mirjalili and Lewis, 2016), Sine Cosine Algorithm (SCA) (Mirjalili, 2016), Harris Hawk Optimization (HHO) (Heidari et al., 2019), Seagull Optimization Algorithm (SOA) (Dhiman and Kumar, 2019), Salp Swarm Algorithm (SSA) (Mirjalili et al., 2016), and Pelican Optimization Algorithm (POA) (Trojovský and Dehghani, 2022) vary in their sensitivity to the structure of test functions. Some of these algorithms perform well on certain functions but do not show consistent behavior across the entire suite. Conversely, PSSS with bandit-based selection produces a more balanced and tighter profile than any other variant. The radar plot shows that PSSS achieves competitive or superior performance in most functions, especially in unimodal and basic categories, aligning well with the numerical trends presented earlier in Table 2, where PSSS-GA with Bandit achieved the best or near-best outcomes for six of seven evaluated functions. These findings suggest that adaptive heuristic coordination, rather than relying on a single metaheuristic, offers more reliable and function-agnostic search behavior. The radar chart further supports this conclusion, emphasizing PSSS's strong performance.

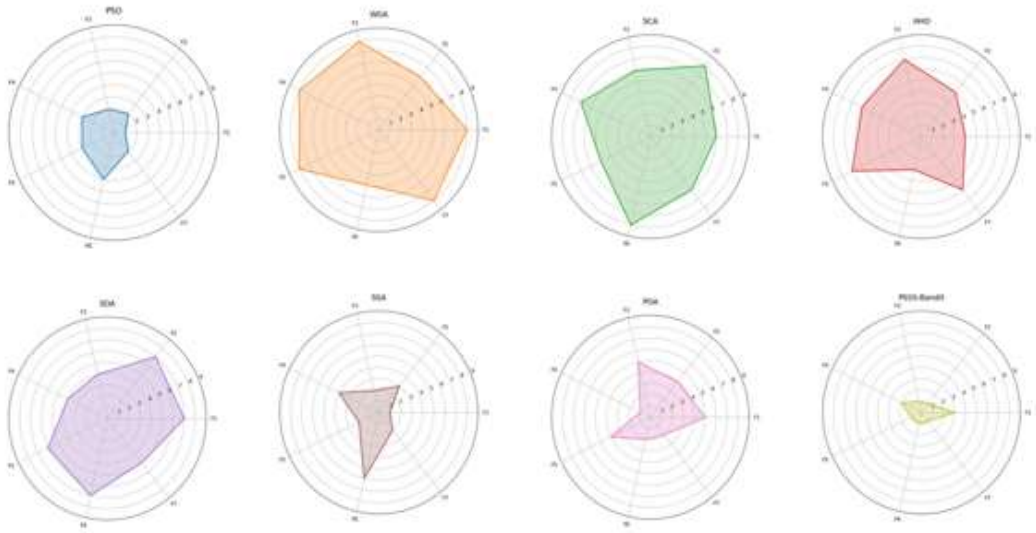

Figure 3: Comparative results of PSSS and other metaheuristic algorithms for CEC 2022 test functions.

4. Conclusions

The present work proposed an improved SSS algorithm by incorporating parallelism and a metaheuristic selection strategy based on learning. Running single-solution-based metaheuristics in parallel reduced the computational time. The second change, replacing random operator selection with bandit-based learning, made the search more adaptive to recent performance. Experiments on CEC 2022 functions F1−F7 demonstrated that both modifications could reduce run time while maintaining or improving solution quality across all function types. Taken together, these results indicate that the improved PSSS variants are more flexible and competitive than the original SSS framework.

There are several directions in which the research can be extended beyond the current study. First, although this work is tested on a subset of the CEC 2022 benchmark suite, it is possible to evaluate the PSSS framework on a larger collection of continuous functions to gain insights into its performance across different types of landscapes. More advanced machine learning methods for the metaheuristic selection process could be explored as another future direction; improving this component may further enhance stability and solution quality. Finally, extending this approach to combinatorial or mixed-integer optimization problems would be a logical next step, as the SSS concept is well-suited for domains where many different local search behaviors are available.

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POZİSYONA BAĞLI KRİTERLERİN AHP YÖNTEMİ İLE ÖNCELİKLENDİRİLMESİ VE BELBİN TAKIM ROLLERİ İLE EŞLEŞTİRİLMESİ: OTOMOTİV SEKTÖRÜ UYGULAMASI

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ÖZET

Bu çalışmada otomotiv sektöründe çapraz fonksiyonel ekiplerin oluşturulmasında teknik yeterlilikler ile davranışsal rol uyumlarının entegrasyonu incelenmiştir. Ekip başarısının yalnızca teknik yeterliliklere dayandırılmasının yetersiz olduğu, pozisyonların gerektirdiği temel kriterlerin davranışsal rollerle birlikte değerlendirilmesi gerektiği varsayımından hareketle, görev tanımları ile Belbin takım rolleri arasındaki uyum sistematik olarak analiz edilmiştir. Araştırmada, pozisyonlara ilişkin teknik kriter ağırlıkları Analitik Hiyerarşi Süreci (AHP) ile belirlenmiş ve çalışanların Belbin rol profilleriyle olan uyumları bu ağırlıklarla karşılaştırmalı olarak değerlendirilmiştir. Bu yaklaşım, ekip kurma süreçlerini sezgisel yargılardan arındırarak daha ölçülebilir, tekrarlanabilir ve nesnel bir yapıya dönüştürmeyi hedeflemektedir. Örnek olarak proje yöneticisi pozisyonunda yapılan analizde, en yüksek uyum gösteren rollerin Takım Oyuncusu, Koordinatör ve Kaynak Araştırıcı (49.52); yedek rollerin ise Şekillendirici, Değerlendirici ve Uygulayıcı (41.10) olduğu belirlenmiştir. Bu sonuç, proje yöneticisi rolünün temel kriterleri olan iletişim ve liderlik gerekliliklerileyle Belbin modelindeki ilgili rollerin güçlü bir tutarlılık gösterdiğini ortaya koymaktadır. Çalışmanın genel bulguları, tüm pozisyonlar için belirlenen öncelikli kriterlerin –örneğin iletişim, liderlik, problem çözme, zaman ve risk yönetimi ve teknik bilgi– ilgili Belbin rollerinin belirlenmesinde belirleyici olduğunu ve görev–rol uyumunun sistematik biçimde oluştuğunu göstermektedir. Analiz sonuçları, AHP ile belirlenen kriter ağırlıkları ile Belbin rol profilleri arasındaki ilişkiyi doğrulamış ve eşleşmelerin yüksek düzeyde tutarlı olduğunu ortaya koymuştur. Sonuç olarak AHP–Belbin entegrasyonu, otomotiv sektöründe çapraz fonksiyonel ekiplerin oluşturulmasında uygulanabilir, tekrarlanabilir ve stratejik bir karar destek mekanizması sunmakta, uygun teknik yetkinliklerin ilgili davranışsal rollerle eşleştirilmesini sağlayarak ekip performansı ve proje başarısını artırmaktadır.

Anahtar Kelimeler: AHP, Belbin Takım Rolleri, Proje Yönetimi, Çapraz Fonksiyonel Ekip

POSITION-BASED CRITERIA PRIORITIZATION USING THE AHP METHOD AND THEIR ALIGNMENT WITH BELBIN TEAM ROLES: AN AUTOMOTIVE INDUSTRY APPLICATION

ABSTRACT

This study examines the integration of technical competencies and behavioral role alignment in the formation of cross-functional teams in the automotive industry. Based on the assumption that relying solely on technical competencies for team success is insufficient, and that fundamental positional criteria should be evaluated alongside behavioral roles, the alignment between job descriptions and Belbin team roles was systematically analyzed. The technical criteria weights for each position were determined using the Analytic Hierarchy Process (AHP), and the compatibility of employees' Belbin role profiles with these weights was comparatively assessed. This approach aims to transform team formation processes into a more measurable, repeatable, and objective structure by eliminating intuitive judgments. As an illustrative example, the analysis of the project manager position identified Teamworker, Coordinator, and Resource Investigator (49.52) as the roles showing the highest compatibility, while Shaper, Monitor Evaluator, and Implementer (41.10) were identified as secondary roles. This finding demonstrates strong coherence between the core requirements of the project manager role—communication and leadership—and the corresponding Belbin roles. The study's overall results indicate that the prioritized criteria determined for all positions, such as communication, leadership, problem-solving, time and risk management, and technical knowledge, decisively influence the identification of relevant Belbin roles, ensuring systematic position–role alignment. The analysis confirmed the relationship between the AHP-determined criteria weights and the Belbin role profiles, demonstrating highly consistent matches. Consequently, the integrated AHP–Belbin model provides a practical, repeatable, and strategic decision-support mechanism for forming cross-functional teams in the automotive industry. By aligning relevant technical competencies with appropriate behavioral roles, it enhances team performance and increases project success.

Keywords: AHP, Belbin Team Roles, Project Management, Cross-Functional Team

1. GİRİŞ

Küreselleşme, dijitalleşme ve müşteri beklentilerindeki hızlı değişim, endüstriyel işletmeleri daha çevik, yenilikçi ve iş birliğine dayalı çalışma modelleri geliştirmeye zorlamaktadır. Özellikle otomotiv sektörü gibi yüksek rekabetin ve sürekli ürün çeşitliliğinin hâkim olduğu alanlarda, organizasyonların başarı düzeyi artık yalnızca teknik kapasiteye değil, aynı zamanda farklı birimlerin etkin koordinasyonuna ve çok disiplinli ekiplerin uyumuna bağlı hale gelmiştir.

Bu bağlamda, literatürde "cross-functional teams" olarak adlandırılan çapraz fonksiyonel takımlar, organizasyonların yenilikçi projeleri başarıyla yürütebilmesinde kilit bir rol üstlenmektedir (Ton, Hammerl, Weber, Kremer, & Szabo-Szentgroti, 2022). Üretim, kalite, mühendislik, tedarik zinciri, planlama ve satış gibi farklı departmanlardan gelen bireylerin bir araya gelmesiyle oluşturulan bu ekipler, bilgi paylaşımını artırarak problemlere çok boyutlu bakış açısı kazandırmakta, süreç içi darboğazları azaltmakta ve proje çıktılarını hızla ticarileştirebilmektedir. Ancak bu yapıların başarısı, ekip üyelerinin yalnızca teknik uzmanlıklarına değil, aynı zamanda iletişim, liderlik, takım uyumu ve problem çözme gibi davranışsal niteliklerine de bağlıdır (Abdolahi, Barmayehvar, Marjani, & Esmaeilabadi, 2023).

Otomotiv sektöründe proje temelli çalışmalar, çoğunlukla kısa zaman dilimlerinde yüksek kalite ve düşük maliyet hedefleri doğrultusunda yürütülmektedir. Bu koşullar altında, her ekip üyesinin hem kendi uzmanlık alanını etkin biçimde kullanması hem de ekip içindeki diğer pozisyonlarla uyum içinde çalışması beklenmektedir. Bu noktada, proje yöneticilerinin en kritik görevi, doğru kişileri doğru pozisyonlara yerleştirerek ekip içi sinerjiyi sağlamaktır. Ancak bu süreç çoğu zaman deneyime dayalı sezgisel kararlarla yürütülmekte, bu da sübjektif sonuçlara ve performans farklılıklarına neden olmaktadır (Kalayathankal, Kureethara, & Narayanamoorthy, 2021).

Dolayısıyla, çapraz fonksiyonel ekiplerin oluşturulmasında teknik yeterliliklerin yanı sıra bireysel davranış eğilimlerinin ve takım içi rollerin de dikkate alınması gerekmektedir. Bu çalışma, bu gereksinimden hareketle, otomotiv sektöründe etkin ekip kurulumuna yönelik analitik ve davranışsal unsurları birlikte ele alan bir yaklaşım geliştirmeyi amaçlamaktadır.

2. ÇALIŞMA ALANI

Çalışma, Türkiye'de otomotiv ana sanayiinde faaliyet gösteren bir üretim tesisinde gerçekleştirilmiştir. Kurum, prototip , numune ve seri üretim süreçlerinin tamamında proje yönetimi, kalite güvencesi, tedarik zinciri yönetimi, üretim planlama, tasarım ve lojistik fonksiyonlarını barındırmaktadır.

Toplam 16 farklı mühendislik ve uzmanlık pozisyonu analiz edilmiştir. Pozisyonlara ilişkin kriterler; İletişim, Liderlik, Zaman ve Risk Yönetimi, Teknik Bilgi ve Problem Çözme olarak belirlenmiştir. Bu kriterlerin literatürde ekip performansını etkileyen temel unsurlar olduğu ve ekip kurma süreçlerinde sıkça vurgulandığı görülmektedir.

Bu çalışmada kullanılan kriterlerin tanımları ve ilgili literatür kaynakları Tablo 1'de özetlenmiştir.

Tablo 1. Literatür Taraması ile Belirlenen Takım Üyesi Seçim Kriterleri

Kriter	Açıklama	Kaynaklar
İletişim	Proje ekibi içinde açık ve etkili bilgi akışının sağlanması, yanlış anlaşılmaların ve iletişim maliyetlerinin azaltılması, ortak bir dil ve standart iletişim protokollerinin oluşturulması.	Hey, 2019; Schmidt, 2013; Boni, Todorova ve Weingart, 2020; Dietz, Pronovost, Mendez-Tellez, Wyskiel, Marsteller, Thompson ve Rosen, 2014; Younis, Sunderraman, Metzler ve Bourgeois, 2021; Super, 2020; Morath, 2006; Da Silva, França, Suassuna, de Sousa Mariz, Rossiley, de Miranda, Gouveia, Monteiro, Lucena, Cardozo ve Espindola, 2013; Abdolahi, Barmayehvar, Marjani ve Esmaeilabadi, 2024; Çulhaoğlu Uludağ, 2022; Kulej-Dudek, 2023; Project Management Institute, 2023
Liderlik	Ekip üyelerinin yönlendirilmesi, motive edilmesi, görev dağılımının dengeli biçimde yapılması ve ekip içindeki sosyal bağların güçlendirilmesi gibi unsurları kapsar.	Hey, 2019; Super, 2020; Boni vd., 2020; Dietz vd., 2014; Morath, 2006; Younis vd., 2021; da Silva vd., 2013; Çulhaoğlu Uludağ, 2022; Kulej-Dudek, 2023; Project Management Institute, 2023
Zaman ve Risk Yönetimi	Karar alma süreçlerinin zamanında yürütülmesi, proje risklerinin analiz edilip yönetilmesi, kaynakların etkin biçimde tahsisi ve performansın izlenmesiyle ilgilidir.	Super, 2020; Schmidt, 2013; Younis vd., 2021; da Silva vd., 2013; Çulhaoğlu Uludağ, 2022; Kulej-Dudek, 2023; Project Management Institute, 2023
Teknik Bilgi	Çalışanın alanında sahip olduğu teknik uzmanlık, mesleki deneyim, eğitim düzeyi ve teknik araçları etkili biçimde kullanma becerisiyle ilgilidir.	Hey, 2019; Boni vd., 2020; Super, 2020; Younis vd., 2021; da Silva vd., 2013; Abdolahi vd., 2024; Çulhaoğlu Uludağ, 2022; Kulej-Dudek, 2023; Project Management Institute, 2023
Problem Çözme	Ekip üyelerinin birlikte çalışarak ortaya çıkan sorunlara çözüm üretebilmesi, çatışmaları yönetebilmesi, koordinasyonu sürdürebilmesi ve iş kalitesini koruyabilmesiyle ilişkilidir.	Hey, 2019; Boni vd., 2020; Dietz vd., 2014; Morath, 2006; Super, 2020; Abdolahi vd., 2024; Kulej-Dudek, 2023; Project Management Institute, 2023

3. MATERYAL VE YÖNTEM

3.1 Veri Toplama

Her pozisyon için, ilgili alanda deneyimli uzmanlardan oluşan karar vericilerle görüşmeler gerçekleştirilmiş ve pozisyonlara ilişkin ikili karşılaştırma matrisleri oluşturulmuştur. Bu matrisler, kriterlerin göreceli önemini belirlemek için kullanılmıştır.

3.2 Analitik Hiyerarşi Prosesi (AHP)

AHP yöntemi, kriter ağırlıklarını belirlemek ve çok kriterli karar problemlerini çözmek amacıyla uygulanmıştır. Tutarlılık oranı (CR) ≤ 0,1 kabul edilerek kararların güvenilirliği sağlanmıştır. Elde edilen kriter ağırlıkları ve CR değerleri Tablo 2'de sunulmuştur.

Tablo 2. Pozisyon Bazında AHP Kriter Ağırlıkları ve Tutarlılık Oranları (CR)

Kriter / Pozisyon	İletişim	Liderlik	Zaman ve Risk Yönetimi	Teknik Bilgi	Problem Çözme	CR
Proje Yöneticisi	24.7605	24.7605	24.7605	9.3825	16.3359	0.0395
Satış Mühendisi	41.1222	17.8995	23.6185	6.4705	10.8894	0.0140
Kalite Güvence Mühendisi	10.0112	6.9961	16.4560	40.9995	25.5372	0.0223
Giriş Kalite Kontrol Mühendisi	10.0112	6.9961	16.4560	40.9995	25.5372	0.0223
Tedarikçi Kalite Kontrol Mühendisi	10.0112	6.9961	16.4560	40.9995	25.5372	0.0223
Tedarik Zinciri Mühendisi	16.2545	8.1272	33.2838	28.9753	13.3592	0.0508
Üretim Planlama Mühendisi	19.8061	7.1597	38.6901	24.0987	10.2454	0.0295
Tasarım Mühendisi	15.1293	6.7636	23.4783	43.1629	11.4659	0.0131
İmalat Mühendisi	8.7454	11.2709	18.9682	37.9364	23.0791	0.0332
Proses Mühendisi	8.7454	11.2709	18.9682	37.9364	23.0791	0.0332
Kalite Kontrol Mühendisi	10.0112	6.9961	16.4560	40.9995	25.5372	0.0223
Üretim Mühendisi	11.8187	6.7881	16.9122	36.6816	27.7995	0.0407
İç Lojistik ve Envanter Yönetimi Uzmanı	26.7781	18.7133	38.3186	5.6922	10.4977	0.0194
Paketleme Mühendisi	13.5047	8.0245	19.3249	33.6465	25.4993	0.0340
Lojistik Uzmanı	12.3341	9.3475	39.1937	17.6497	21.4749	0.0427
Final Kalite Mühendisi	10.0112	6.9961	16.4560	40.9995	25.5372	0.0223

3.3 Belbin Takım Rolleri Entegrasyonu

Belbin Takım Rolleri (Belbin, 2010), ekip üyelerinin davranışsal eğilimlerini değerlendirmek için kullanılmıştır. İlk olarak kriterler, Belbin rollerinin öne çıkan özellikleri ile Tablo 3'te eşleştirilmiştir.

Tablo 3. Belbin Takım Rolleri ve Ekip Üyesi Seçim Kriterleri ile Eşleştirilmesi

Belbin Takım Rolü	Öne Çıkan Kriterleri
Değerlendirici (Monitor Evaluator)	Problem Çözme, Zaman ve Risk Yönetimi
Fikir Üretici (Plant)	Problem Çözme, Teknik Bilgi
Kaynak Araştırıcısı (Resource Investigator)	İletişim, Liderlik
Uzman (Specialist)	Teknik Bilgi, Problem Çözme
Takım Oyuncusu (Teamworker)	İletişim, Liderlik
Koordinatör (Coordinator)	Liderlik, İletişim
Tamamlayıcı / Bitirici (Completer Finisher)	Zaman ve Risk Yönetimi, Teknik Bilgi
Uygulayıcı (Implementer)	Zaman ve Risk Yönetimi, Problem Çözme
Şekillendirici (Shaper)	Liderlik, Problem Çözme

AHP çıktılarından elde edilen kriter önem ağırlıkları, Belbin takım rolleriyle eşleştirilerek her pozisyona karşılık gelen baskın takım rolleri belirlenmiştir. Bu süreçte her rolün öne çıkan kriterleri temel alınmış ve her mühendislik pozisyonu için en uygun Belbin rolleri hesaplanmıştır. Elde edilen puanlar Tablo 4'te gösterilmektedir.

Tablo 4. Ekip Pozisyonlarının Belbin Takım Rolleri Puanları

Belbin Takım Rolü / Pozisyon	**Uzman (Specialist)**	**Uygulayıcı (Implementer)**	**Şekillendirici (Shaper)**	**Koordinatör (Coordinator)**	**Takım Oyuncusu (Teamworker)**	**Kaynak Araştırıcı (RI)**	**Fikir Üretici (Plant)**	**Değerlendirici (Evaluator)**	**Tamamlayıcı/Bitirici (Completer Fin.)**
Proje Yöneticisi	25.7184	41.0964	41.0964	49.5211	49.5211	49.5211	25.7184	41.0964	34.1430
Satış Mühendisi	17.3599	34.5079	28.7889	59.0216	59.0216	59.0216	17.3599	34.5079	30.0890
Kalite Güvence Mühendisi	66.5366	23.4521	32.5333	17.0074	17.0074	17.0074	66.5366	41.9932	57.4555

Giriş Kalite Kontrol Mühendisi	66.5366	41.9932	32.5333	17.0074	17.0074	17.0074	66.5366	41.9932	57.4555
Tedarikçi Kalite Kontrol Mühendisi	66.5366	41.9932	32.5333	17.0074	17.0074	17.0074	66.5366	41.9932	57.4555
Tedarik Zinciri Mühendisi	42.3344	46.6430	21.4864	24.3817	24.3817	24.3817	42.3344	46.6430	62.2591
Üretim Planlama Mühendisi	34.3441	48.9354	17.4051	26.9659	26.9659	26.9659	34.3441	48.9354	62.7888
Tasarım Mühendisi	54.6288	34.9442	18.2295	21.8929	21.8929	21.8929	54.6288	34.9442	66.6412
İmalat Mühendisi	61.0155	42.0473	34.3501	20.0163	20.0163	20.0163	61.0155	42.0473	56.9046
Proses Mühendisi	61.0155	42.0473	34.3501	20.0163	20.0163	20.0163	61.0155	42.0473	56.9046
Kalite Kontrol Mühendisi	66.5366	41.9932	32.5333	17.0074	17.0074	17.0074	66.5366	41.9932	57.4555
Üretim Mühendisi	64.4810	44.7116	34.5875	18.6068	18.6068	18.6068	64.4810	44.7116	53.5938
İç Lojistik ve Envanter Yönetimi Uzmanı	16.1900	48.8164	29.2110	45.4914	45.4914	45.4914	16.1900	48.8164	44.0109
Paketleme Mühendisi	59.1459	44.8242	33.5238	21.5293	21.5293	21.5293	59.1459	44.8242	52.9714
Lojistik Uzmanı	39.1247	60.6687	30.8224	21.6816	21.6816	21.6816	39.1247	60.6687	56.8435
Final Kalite Mühendisi	66.5366	41.9932	32.5333	17.0074	17.0074	17.0074	66.5366	41.9932	57.4555

Tablo 5'te otomotiv sektöründe analiz edilen tüm pozisyonların Belbin Takım Rolleri ile uyum düzeylerini ve rol profillerini göstermektedir. Tablo 5, her pozisyon için birinci (en yüksek) ve ikinci (yedek) rolleri belirlemekte ve rolün temel özelliklerini özetlemektedir. Bu sayede ekip kurulumunda pozisyonların teknik ve davranışsal gereklilikleri ile uygun Belbin rolleri arasındaki ilişki net bir şekilde görülebilmektedir.

Tablo 5. Pozisyonlara Göre Birincil ve İkincil Belbin Rol Dağılımları ve Profil Özeti (Pozisyon - Rol Tablosu)

Pozisyon	1. Rol (En Yüksek Rol)	2. Rol (Yedek Rol)	Rol Profili Özeti
Proje Yöneticisi	Takım Oyuncusu / Koordinatör / Kaynak Araştırıcı (49.52)	Şekillendirici / Değerlendirici / Uygulayıcı (41.09)	İletişim, koordinasyon ve ekip uyumuna odaklı, yönlendirici lider.
Satış Mühendisi	Takım Oyuncusu / Koordinatör / Kaynak Araştırıcı (59.02)	Değerlendirici / Uygulayıcı (34.5)	İlişki yönetimi güçlü, insan odaklı, sosyal ve motive edici.
Kalite Güvence Mühendisi	Uzman / Fikir Üretici (66.54)	Tamamlayıcı/Bitirici (57.45)	Analitik, detaycı, sistematik; kaliteyi ve doğruluğu önceler.
Giriş Kalite Kontrol Mühendisi	Uzman / Fikir Üretici (66.54)	Tamamlayıcı/Bitirici (57.45)	Standartlara bağlı, düzenli ve metodik çalışma tarzına sahip.
Tedarikçi Kalite Kontrol Mühendisi	Uzman / Fikir Üretici (66.54)	Tamamlayıcı/Bitirici (57.45)	Kalite güvence süreçlerinde analitik ve dikkatli bir uzman.
Tedarik Zinciri Mühendisi	Tamamlayıcı/Bitirici (62.26)	Uygulayıcı / Değerlendirici (46.64)	Planlı, süreç odaklı, sistemli; ekip çalışmasında da uyumlu.
Üretim Planlama Mühendisi	Tamamlayıcı/Bitirici (62.79)	Değerlendirici / Uygulayıcı (48.94)	Zaman ve kaynak yönetiminde güçlü, düzenli ve sonuç odaklı.
Tasarım Mühendisi	Tamamlayıcı/Bitirici (66.64)	Uzman / Fikir Üretici (54.63)	Yaratıcı ama aynı zamanda detaycı; teknik kaliteye önem veren.
İmalat Mühendisi	Uzman / Fikir Üretici (61.02)	Tamamlayıcı/Bitirici (56.90)	Teknik açıdan güçlü, üretim süreçlerinde pratik ve sistemli.
Proses Mühendisi	Uzman / Fikir Üretici (61.02)	Tamamlayıcı/Bitirici (56.90)	Süreç geliştirme ve analizde başarılı, sistematik düşünen.
Kalite Kontrol Mühendisi	Uzman / Fikir Üretici (66.54)	Tamamlayıcı/Bitirici (57.45)	Detaycı, standartlara bağlı, kalite güvencesinde titiz.
Üretim Mühendisi	Uzman / Fikir Üretici (64.48)	Tamamlayıcı/Bitirici (53.59)	Teknik uzmanlık yüksek, süreç iyileştirmede becerikli.
İç Lojistik ve Envanter Yönetimi Uzmanı	Uygulayıcı / Değerlendirici (48.81)	Koordinatör / Takım Oyuncusu / Kaynak Araştırıcı (45.49)	İnsan ilişkilerinde güçlü, planlama ve analiz yönü de kuvvetli.
Paketleme Mühendisi	Uzman / Fikir Üretici (59.15)	Tamamlayıcı/Bitirici (52.97)	Kaliteyi ve düzeni ön planda tutan sistematik çalışan.
Lojistik Uzmanı	Uygulayıcı / Değerlendirici (60.67)	Tamamlayıcı/Bitirici (56.84)	Analitik, planlı ve süreç verimliliğine odaklı.
Final Kalite Mühendisi	Uzman / Fikir Üretici (66.54)	Tamamlayıcı/Bitirici (57.45)	Kalite kontrol süreçlerinde disiplinli ve metodik çalışan.

4. SONUÇ

Bu çalışmada, çapraz fonksiyonel ekiplerin oluşturulmasında AHP ve Belbin entegrasyonu kullanılarak sistematik bir karar destek modeli geliştirilmiştir. Araştırmada, ekip üyelerinin seçiminde dikkate alınması gereken teknik bilgi, problem çözme, zaman ve risk yönetimi, iletişim ve liderlik kriterleri belirlenmiş ve AHP yöntemiyle göreceli ağırlıkları hesaplanmıştır.

Elde edilen bulgular, modelin, görevlerin niteliğine uygun seçimler yapılmasını desteklediğini ve ekip üyelerinin pozisyonlara atanmasında hangi kriterlerin öncelikli olduğunu açıkça ortaya koyduğunu göstermektedir. Bu yaklaşım sayesinde, takım oluşturma süreci sistematik, nesnel ve tekrarlanabilir bir şekilde yürütülebilmekte, çok disiplinli projelerde ekip verimliliği ve proje başarısı artırılabilmektedir. Ayrıca, model farklı pozisyonlar ve kriterler için esnek bir şekilde uygulanabilir olmasıyla, ekip planlamasında yöneticilere pratik bir araç sağlamaktadır.

5. LİTERATÜRE KATKI

Bu çalışmada, otomotiv sektöründe ekip oluşturma süreçlerinde hem teknik yeterliliklerin hem de davranışsal rollerin eş zamanlı olarak değerlendirilmesine imkân sağlamaktadır. Literatürde genellikle ÇKKV yöntemleri ve Belbin takım rolleri ayrı ayrı incelenmişken, bu çalışmada Analitik Hiyerarşi Prosesi (AHP) ile pozisyonlara bağlı kriter ağırlıkları belirlenmiş ve Belbin Takım Rolleri ile entegrasyonu gerçekleştirilmiştir.

Bu yaklaşım, teknik bilgi, iletişim, liderlik, zaman ve risk yönetimi ile problem çözme gibi kritik kriterlerini Belbin rolleri ile nasıl ilişkilendiğini ortaya koyarak, pozisyon–rol uyumunu sistematik bir şekilde göstermektedir. Böylece, hem akademik literatüre katkı sağlamakta hem de otomotiv sektöründe proje yönetimi için pratik bir karar destek modeli sunmaktadır.

Ayrıca, çalışmanın yöntemi farklı sektörler için de uyarlanabilir nitelikte olup, ekip oluşturma ve rol dağılımı konularında literatürdeki boşlukları doldurmaya yardımcı olmaktadır.

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İSTANBUL İLÇELERİNDE TEHLİKELİ MADDE DEPO VE TESİSLERİNİN KÜMELEME ANALİZİ VE AFET RİSKİ DEĞERLENDİRMESİ

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ÖZET

Bu çalışma, İstanbul'daki tehlikeli madde depo ve tesislerinin mekânsal dağılımını inceleyerek bu tesislerin afet ve özellikle deprem riski ile ilişkisini analiz etmeyi amaçlamaktadır. İstanbul'un 27 ilçesi üzerinde yürütülen araştırmada, kimya, depolama, atık bertaraf, enerji ve toptan ticaret tesisleri ile nüfus yoğunluğu ve deprem riski değişkenleri kullanılmıştır. Çalışmanın temel amacı, ilçeler arasındaki benzerlikleri ortaya koymak ve tehlikeli madde tesis yoğunluğunun afet riskiyle nasıl örtüştüğünü belirlemektir. Veriler üzerinde yapılan ön işlemler kapsamında eksik değerler giderilmiş, değişkenler Min–Max normalizasyonu yöntemiyle 0–1 aralığına dönüştürülmüştür. İlçeler arasındaki benzerliklerin ölçülmesinde Öklid uzaklığı kullanılmış ve hiyerarşik kümeleme analizi yöntemi uygulanmıştır. Optimum küme sayısı, Elbow yöntemi ve Davies–Bouldin indeksi kullanılarak dört olarak belirlenmiştir. Küme 1 düşük, küme 2 nispeten yüksek, küme 3 yüksek ve küme 4 ise en yüksek risk profilini temsil etmektedir. Kümeler oluşturulduktan sonra temel bileşen analizi yapılmış bileşen 1 sanayi ve tesis yoğunluklarını bileşen 2 ise deprem ve nüfus yoğunluğunu temsil etmiştir. Analiz sonucunda bileşen 1 varyansı %58, bileşen 2 varyansı %27 oranında çıkmış toplam veri değişkeninin %85'ini temsil etmiştir. Elde edilen sonuçlar, İstanbul ilçelerinin tehlikeli madde tesis yoğunluğu, nüfus büyüklüğü ve deprem riski bakımından çeşitli benzerlik ve farklılıklar gösterdiğini ortaya koymuştur. Tuzla en yüksek risk grubunda, Esenyurt ve Başakşehir gibi sanayi yoğunluğu yüksek olan ilçeler yüksek risk grubunda, Bahçelievler, Esenler ve Fatih gibi nüfus yoğunluğu yüksek olan ilçeler afet risk grubunda, Silivri ise düşük risk grubunda yer almıştır. Bu bilgiler, yerel yönetimlerin ve lojistik planlamacıların afet ve risk yönetimi alanında yürütecekleri çalışmalarına katkılar sağlayacaktır.

Anahtar Kelimeler: Tehlikeli Madde, Kümeleme Analizi, Afet Riski, Risk Yönetimi, İstanbul

CLUSTERING ANALYSIS OF HAZARDOUS MATERIAL STORAGE FACILITIES AND DISASTER RISK ASSESSMENT IN ISTANBUL DISTRICTS

ABSTRACT

This study aims to examine the spatial distribution of hazardous material storage facilities and industrial sites in Istanbul and to analyze their relationship with disaster risk, particularly earthquake risk. The research was conducted across 27 districts of Istanbul using variables such as chemical facilities, storage units, waste treatment plants, energy facilities, wholesale trade establishments, population density, and earthquake risk levels. The main objective of the study is to identify similarities among districts and determine how the concentration of hazardous material facilities aligns with disaster risk. During the preprocessing stage, missing values were addressed, and all variables were normalized to the 0–1 range using the Min–Max normalization method. Euclidean distance was used to measure similarities between districts, and hierarchical clustering analysis was applied. The optimal number of clusters was determined as four based on the Elbow method and the Davies–Bouldin index. Cluster 1 represents low risk, Cluster 2 relatively higher risk, Cluster 3 high risk, and Cluster 4 the highest risk profile. After forming the clusters, Principal Component Analysis was performed, where Component 1 represented industrial and facility density, while Component 2 represented earthquake and population density. The analysis indicated that Component 1 explained 58% of the variance, Component 2 explained 27%, and together they accounted for 85% of the total data variability. The findings reveal significant similarities and differences among Istanbul districts in terms of hazardous material facility density, population levels, and earthquake risk. Tuzla was identified as the highest-risk district; Esenyurt and Başakşehir, with high industrial density, were grouped in the high-risk category; Bahçelievler, Esenler, and Fatih, characterized by high population density, were classified within the disaster risk group; while Silivri was identified as the low-risk district. These insights are expected to support local authorities and logistics planners in their disaster and risk management efforts.

Keywords: Hazardous Materials, Clustering Analysis, Disaster Risk, Risk Management, Istanbul

1. GİRİŞ

Tesis konumlarının belirlenmesi, bir kuruluş açısından önemli bir stratejik karardır ve bu süreci tanımlayan yaklaşım konum stratejisi olarak adlandırılır. Bu tür kararlar genellikle uzun vadeli etkiler doğurur ve alınan kararlardan geri dönülmesi oldukça güçtür. Genel olarak, farklı kuruluşların konum seçiminde benzer unsurlar dikkate alınsa da her işletme faaliyet gösterdiği sektörün gereksinimleri doğrultusunda kendine özgü bir yer seçimi stratejisi uygular. (Fuskova, Hanáčková & Gubáňová, 2018, s. 5). İstanbul, Türkiye'nin ekonomik ve sanayi merkezi olması sebebiyle tehlikeli madde faaliyetlerinin yoğunlaştığı bir metropol konumundadır. Kentte bulunan kimya, enerji, atık bertaraf ve depolama tesislerinin bir kısmı, yüksek nüfus yoğunluğuna sahip bölgelerde yer almakta ve bu durum, olası bir deprem veya endüstriyel kazanın olumsuz etkilerini artırmaktadır. Kimyasal tehditler toksik endüstriyel kimyasalların yayılması, ulusal düzeyde önemli bir afet senaryosu olarak değerlendirilmektedir. Bu çerçevede, tehlikeli madde tesislerinin yoğunluk düzeylerinin belirlenmesi, afet yönetimi ve risk azaltma politikaları için kritik bir önceliktir.

Tehlikeli madde lojistiği, yalnızca tesis güvenliğiyle sınırlı kalmayıp; yerleşim alanlarına uzaklık, nüfus yoğunluğu, deprem riski ve acil tahliye planlarının uygulanabilirliği gibi çok boyutlu faktörlerin birlikte ele alınmasını gerektirmektedir (Demirci, Ateş & Fandaklı, 2023, ss. 244–245). Bu nedenle, istatistiksel yöntemlerin kullanılması, veriler arasındaki ilişkilerin nesnel biçimde analiz edilmesine ve risk bölgelerinin sınıflandırılmasına olanak tanımaktadır.

Bu çalışmada, İstanbul'daki tehlikeli madde depo ve tesisleri, nüfus yoğunluğu ve deprem riski değişkenleri birlikte dikkate alınarak hiyerarşik kümeleme analizi yöntemiyle değerlendirilmiştir. İlçeler arasındaki benzerlikler Öklid uzaklığı yöntemiyle ölçülmüş, optimum küme sayısı Elbow (Dirsek) yöntemi ve Davies–Bouldin indeksiyle belirlenmiştir. Analiz sonucunda ilçeler, tehlikeli madde tesis yoğunluğu, nüfus büyüklüğü ve afet riski bakımından farklı kümelere ayrılmıştır.

Bu yönüyle çalışma, İstanbul'da tehlikeli madde lojistiği ve afet riski arasındaki ilişkiyi bütüncül bir yaklaşımla ortaya koymakta; afet planlaması, risk azaltma stratejileri ve tesis yer seçimi süreçlerine bilimsel bir temel sunmaktadır.

2. YÖNTEM

Bu çalışmada, İstanbul ilçelerindeki tehlikeli madde depo ve tesislerinin afet ve özellikle deprem riski ile ilişkisini belirlemek amacıyla kümeleme analizi yöntemi kullanılmıştır. Bu yöntem, ilçelerin belirli kriterler doğrultusunda benzerlik düzeylerini ölçerek, birbirine yakın özellikler gösteren bölgeleri aynı kümede toplamayı amaçlamaktadır.

2.1. Veri Seti ve Değişkenler

Analizde İstanbul'un 27 ilçesine ait veriler değerlendirilmiştir. Veri setinde yer alan değişkenler şunlardır:

- Kimya tesisleri (adet)
- Depolama alanları (adet)
- Atık bertaraf tesisleri (adet)
- Enerji tesisleri (adet)
- Toptan ticaret tesisleri (adet)
- Nüfus yoğunluğu (kişi/km²)

- Deprem riski (düşük, orta, yüksek)

Farklı ölçeklerdeki değişkenlerin karşılaştırılabilir hale gelmesi için sayısal veriler Min–Max normalizasyonu yöntemiyle 0–1 aralığına dönüştürülmüştür. Deprem riski değişkeni ise kategorik olup düşük, orta ve yüksek olarak sınıflandırılmıştır.

2.2. Analiz Yöntemi

İlçeler arasındaki benzerliklerin belirlenmesinde Öklid uzaklığı ölçütü kullanılmıştır. Bu ölçüt, her bir ilçenin diğerleriyle olan farklılık düzeyini sayısal olarak ifade etmektedir. Elde edilen uzaklık matrisi temel alınarak, hiyerarşik kümeleme analizi yöntemi uygulanmıştır (Taşkın & Emel, 2010, s. 398). Bu yöntem, ilçeleri benzerlik düzeylerine göre kademeli olarak birleştirerek kümeler arasındaki yapısal ilişkileri hiyerarşik biçimde ortaya koymaktadır (Rani & Rohil, 2013, s. 1227). Küme sayısı belirlendikten sonra temel bileşen analizi uygulanmıştır. Temel Bileşen Analizi, ilk olarak 1901 yılında Karl Pearson tarafından ortaya konulmuş, 1933 yılında ise Harold Hotelling tarafından geliştirilmiştir. Bu yöntem, çok sayıda birbiriyle ilişkili değişken içeren veri setlerinin boyutlarını, verideki toplam değişkenlik (varyans) mümkün olduğunca korunarak daha az sayıda bileşene indirgemeyi amaçlayan bir istatistiksel dönüşüm tekniğidir (Yazar, Yavuz & Çay, 2009, s. 51).

2.3. Küme Sayısının Belirlenmesi

Kümeleme analizinde uygun küme sayısının belirlenmesi büyük önem taşımaktadır. Bu çalışmada optimum küme sayısı, iki farklı yöntemle değerlendirilmiştir:

Elbow Yöntemi: Küme içi hata kareleri toplamı grafiğindeki kırılma noktası optimal küme sayısını göstermektedir (Özarı & Can, 2023, s. 3).Davies–Bouldin İndeksi: Küme içi benzerliklerin maksimum, kümeler arası farklılıkların minimum olduğu yapıyı temsil eden bu indeks, düşük değerlerde daha başarılı bir kümeleme sonucuna işaret etmektedir (Cingiz & Marangoz, 2021, s. 454).

Her iki ölçüt birlikte değerlendirildiğinde, İstanbul ilçelerinin dört kümeye ayrılmasının veriyi en iyi şekilde temsil ettiği sonucuna ulaşılmıştır.

2.3.1. Temel Bileşen Analizi

Temel bileşen analizi İstanbul'un 27 ilçesine ait yedi değişkenin kimya tesisleri, depolama alanları, atık bertaraf tesisleri, enerji tesisleri, toptan ticaret tesisleri, nüfus yoğunluğu ve deprem riski daha az sayıda bağımsız eksen altında özetlenmesi amacıyla uygulanmıştır. Analiz öncesinde tüm sayısal değişkenler Min–Max normalizasyonu yöntemiyle 0–1 aralığına dönüştürülmüş, böylece farklı ölçeklerdeki veriler karşılaştırılabilir hale getirilmiştir.

Tablo 2.3.1.1. Bileşen yükleri

Değişken	Bileşen 1	Bileşen 2
Kimya	0.91	0.10
Depolama	0.88	0.12
Atık Bertaraf	0.85	0.04
Enerji	0.79	0.08
Toptan Ticaret	0.83	0.14
Nüfus Yoğunluğu	0.09	0.93
Deprem Riski	0.15	0.88

Temel bileşen analizinde öncelikle değişkenler arası ilişkileri gösteren kovaryans matrisi oluşturulmuş, ardından bu matrisin özdeğerleri ve özvektörleri hesaplanmıştır. En yüksek özdeğerler, verideki varyansın en büyük kısmını açıklayan bileşenleri temsil etmektedir. Bu kapsamda, çalışmada ilk iki bileşen, toplam varyansın büyük kısmını açıklamaktadır.

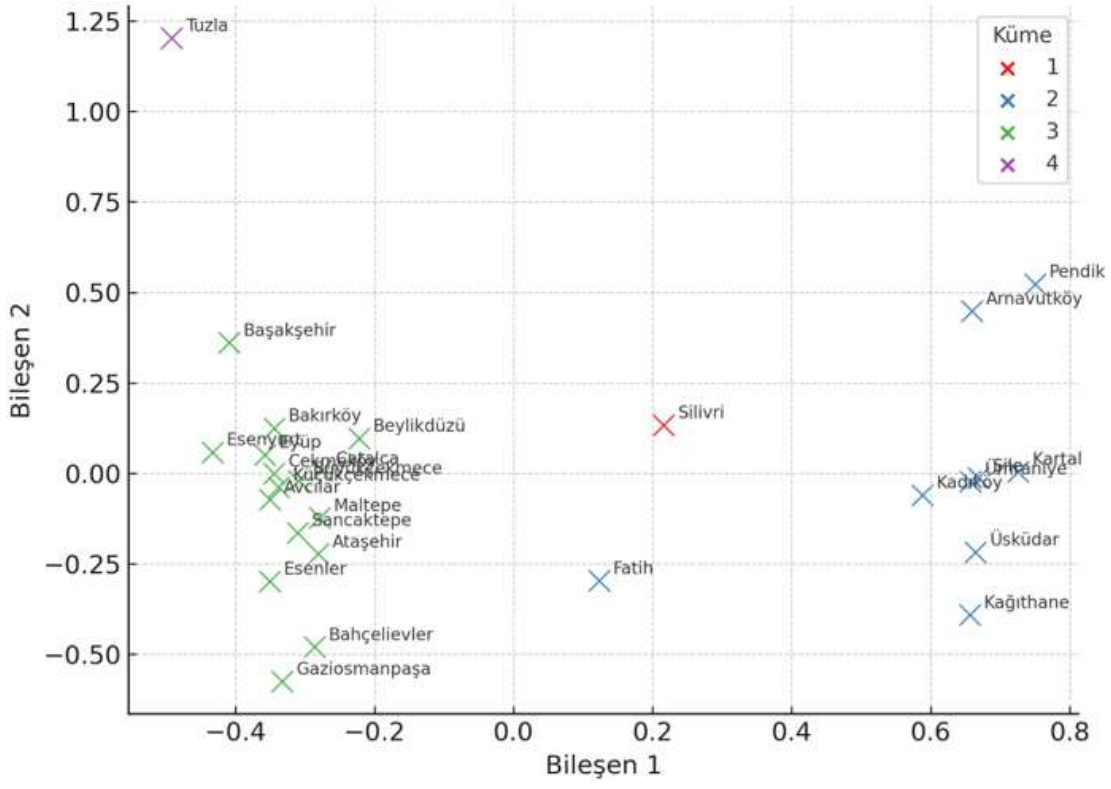
Tablo 2.3.1.2. Varyans oranları

Bileşen	Özdeğer	Açıklanan Varyans (%)	Kümülatif Varyans (%)
Bileşen 1	4.75	67.8	67.8
Bileşen 2	1.22	17.3	85.1
Bileşen 3	0.48	6.8	91.9
Bileşen 4	0.3	-	-

Temel bileşen analizi sonuçlarına göre ilk 2 bileşen toplam varyansın %85.1'ini açıklamaktadır. Üçüncü bileşenin özdeğeri 1'in altında olup yalnızca %6.8'lik bir ek varyans katkısı bulunmaktadır. Bu nedenle literatürde yaygın olarak kabul edilen Kaiser kriteri doğrultusunda üçüncü bileşen modele dahil edilmemiş, analizler iki temel bileşen üzerinden gerçekleştirilmiştir.

2.4. Kümeleme

Veriler ilk işleme adımlarının uygulanmasının ardından kümeler Python ortamına aktarılmış ve hiyerarşik kümeleme sonuçları kullanılarak görsel bir grafik oluşturulmuştur. Böylece ilçeler arası benzerlik yapısı, kümeleşme sırası ve kümeler arası mesafeler grafik olarak ortaya konmuştur.



Şekil 2.4.1. İstanbul ilçeleri kümeleme sonuçları

Elde edilen kümeleme işlemi sonuçlarına ait grafik incelendiğinde aşağıdaki bulgular gözlemlenmektedir.

- Tuzla, grafiğin üst kısmında tekil bir konumda yer almakta ve yüksek sanayi yoğunluğu ile yüksek risk düzeyini temsil etmektedir. Bu durum, ilçedeki kimya, depolama ve enerji tesislerinin yoğunluğundan kaynaklanmaktadır.
- Arnavutköy, Pendik ve Kartal grafiğin sağ tarafında yer almakta ve sanayi yoğunluğunu temsil eden eksen yönünde yüksek değerlere sahiptir. Bu ilçeler, üretim ve lojistik faaliyetlerin belirgin olduğu sanayi odaklı alanlar olarak öne çıkmaktadır.
- Fatih, grafiğin merkezine yakın bir konumda bulunmakta olup ortalama sanayi yoğunluğu ve yüksek nüfus baskısı ile kentsel risk profiline sahiptir.
- Başakşehir, Esenyurt ve Küçükçekmece, grafikte yeşil kümeyi oluşturan yoğun noktalar olarak görünmekte hem yüksek nüfus hem de yüksek deprem riski nedeniyle yüksek risk grubunda yer almaktadır.
- Silivri, grafikte diğer ilçelerden ayrışmış şekilde konumlanmakta olup düşük nüfus ve tesis yoğunluğu nedeniyle tek başına düşük risk profili sergileyen bir ilçedir.
- Şile, çok düşük nüfus ve tesis yoğunluğu ile en düşük risk seviyesine sahip ilçelerden biri olup, düşük afet ve lojistik risk profili göstermektedir.

Tablo 2.4.1. İstanbul ilçelerinin hiyerarşik kümeleme analizi sonucunda oluşan gruplarını göstermektedir.

Tablo 2.4.1. İstanbul ilçeleri hiyerarşik kümeleme tablosu

Küme No	Küme Rengi	İlçeler
1	Kırmızı	Silivri
2	Mavi	Arnavutköy, Pendik, Kartal, Ümraniye, Üsküdar, Kadıköy, Kağıthane, Şile,
3	Yeşil	Başakşehir, Bakırköy, Beylikdüzü, Küçükçekmece, Çekmeköy, Ataşehir, Bahçelievler, Gaziosmanpaşa, Esenler, Esenyurt, Avcılar, Maltepe, Sancaktepe, Eyüp, Fatih, Çatalca, Büyükçekmece
4	Mor	Tuzla

Küme 1 ve Küme 4, farklı özellikler gösterdikleri için ayırt edici bölgeler olarak öne çıkmaktadır. Küme 2 ve Küme 3 ise benzer özelliklere sahip çok sayıda ilçeyi kapsamaktadır. Bu durum, İstanbul'daki risk dağılımının hem sanayi yoğunluğu hem de nüfus ve afet etkisi açısından çift yönlü bir yapı sergilediğini göstermektedir.

2.5. Önerilen Analize Ait Uygulama Adımları

Analiz süreci aşağıdaki adımlar doğrultusunda gerçekleştirilmiştir:

1. Veri Matrisinin Oluşturulması: İlçeler satır, değişkenler sütun olacak şekilde veri seti düzenlenmiştir.

2. Verilerin Normalizasyonu: Farklı ölçeklerdeki veriler 0–1 aralığına dönüştürülmüştür.

3. Benzerlik Matrisi Oluşturulması: İlçeler arasındaki benzerlik düzeyleri Öklid uzaklığı formülüyle hesaplanmıştır.

4. Hiyerarşik Kümeleme Uygulaması: Benzerlik matrisine göre ilçeler kümelere ayrılmıştır.

5. Optimum Küme Sayısının Belirlenmesi: Elbow ve Davies–Bouldin yöntemleri birlikte kullanılarak ideal küme sayısı tespit edilmiştir.

6. Temel Bileşen Analizi uygulanarak, İstanbul ilçelerindeki çok boyutlu veriler iki temel bileşen altında özetlenmiş ve sanayi yoğunluğu ile afet risk düzeyleri arasındaki ilişki istatistiksel olarak ortaya konmuştur.

7. Sonuçların Yorumlanması: Elde edilen kümeler, tehlikeli madde tesis yoğunluğu, nüfus büyüklüğü ve deprem riski değişkenleri açısından değerlendirilmiştir.

2.6. Yöntemin Katkısı

Hiyerarşik kümeleme yöntemi, İstanbul ilçelerinin tehlikeli madde tesis yoğunluğu ve afet riskleri bakımından benzerlik ve farklılıklarını istatistiksel olarak sınıflandırarak risk gruplarını net bir biçimde ortaya koymuştur. Bu yöntem sayesinde ilçeler arasındaki mekânsal risk profilleri belirlenmiş; afet yönetimi, acil müdahale, risk azaltma ve tesis yer seçimi gibi kritik süreçlere bilimsel bir karar destek altyapısı sunulmuştur. Elde edilen kümeler, hem mevcut tehlikeli madde lojistik ağının analiz edilmesine hem de geleceğe yönelik stratejik planlamaların daha rasyonel biçimde yapılmasına katkıda bulunmuş böylece, afet planlaması, risk azaltma ve tesis yer seçimi gibi karar süreçlerine bilimsel bir temel sağlanmıştır.

3. SONUÇ

- Analiz sürecinde hiyerarşik kümeleme yöntemi uygulanmış optimum küme sayısı Elbow yöntemi ve Davies Bouldin indeksiyle 4 olarak benimsenmiştir. Elde edilen sonuçlar, İstanbul ilçelerinin tehlikeli madde tesis yoğunluğu, nüfus büyüklüğü ve deprem riski bakımından belirgin biçimde farklı kümelerde toplandığını ortaya koymuştur.

- Yüksek sanayi yoğunluğuna sahip Tuzla, Esenyurt ve Başakşehir gibi ilçeler, tehlikeli madde lojistiği açısından yüksek risk grubunda yer alırken; yüksek nüfus yoğunluğu ve deprem riskiyle öne çıkan Bahçelievler, Esenler ve Fatih gibi ilçeler afet sırasında daha yüksek etki düzeyine sahiptir. Buna karşın Şile, Çatalca ve Silivri ilçeleri, düşük nüfus ve tesis yoğunluğu nedeniyle görece daha güvenli bölgeler olarak değerlendirilmiştir.

- Bu bulgular, tehlikeli madde tesislerinin yalnızca ekonomik ve lojistik kriterlerle değil, afet risk göstergeleriyle birlikte ele alınması gerektiğini göstermektedir. Özellikle sanayi yoğunluğu ile nüfus baskısının birleştiği alanlarda riskin çarpan etkisiyle arttığı tespit edilmiştir. Bu durum, afet yönetimi ve kentsel planlama süreçlerinde bütünleşik bir yaklaşımın gerekliliğini ortaya koymaktadır.

- Yüksek riskli ilçelerde (örneğin Tuzla, Esenyurt, Başakşehir), tehlikeli madde tesisleri için düzenli denetim mekanizmaları kurulmalı, acil müdahale planları güncellenmelidir.

- Yüksek nüfus yoğunluğuna sahip bölgelerde, yeni tesis yatırımları sınırlandırılmalı ve alternatif, düşük riskli bölgeler tercih edilmelidir.
- Orta riskli ilçelerde, mevcut tesislerin güvenlik altyapısı güçlendirilmeli, olası afet senaryolarına göre risk azaltma tatbikatları yapılmalıdır.
- Düşük riskli ilçeler, gelecekteki tesis yer seçimi için alternatif güvenli alanlar olarak değerlendirilmelidir.
- Kamu kurumları ile özel sektör arasında veri paylaşımı ve risk iletişimi artırılarak, entegre bir tehlikeli madde yönetim sistemi oluşturulmalıdır.
- Sonuç olarak, bu çalışma İstanbul'da tehlikeli madde lojistiği ile afet riski arasındaki ilişkiyi bütüncül bir biçimde ele almış ve karar vericiler için bilimsel bir yol haritası sunmuştur. Bulgular, sürdürülebilir kentsel planlama, afet yönetimi ve endüstriyel güvenlik stratejilerinin geliştirilmesinde temel bir referans niteliği taşımaktadır.

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METAL KESİM MAKİNELERİ İÇİN VERİ GÜVENLİĞİ ODAKLI, AGENT MİMARİLİ AKILLI ASİSTAN GELİŞTİRİLMESİ

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ÖZET

Metal işleme endüstrisinde üretim verimliliği; operatörlerin makine hakimiyetine, teknik bilgiye erişim hızına ve olası arızalara karşı proaktif müdahale yeteneğine doğrudan bağlıdır. Ancak teknik prosedürlerin ve hata giderme talimatlarının dağınık kaynaklarda bulunması, tecrübeli personel eksikliğiyle birleştiğinde; hatalı parametre kullanımı, şerit ve daire testere ömrünün azalması ve plansız makine duruşları gibi maliyetli sorunlara yol açmaktadır. Bu çalışma, metal kesim makineleri için geliştirilmiş, veri güvenliği gereksinimleri nedeniyle tamamen yerel ağda (on-premise) çalışan Büyük Dil Modeli (LLM) tabanlı bir akıllı asistan sistemini sunmaktadır.

Proje kapsamında, teknik servis formları, kullanım kılavuzları ve makine loglarından oluşan toplam 1.822 adetlik özelleştirilmiş bir veri seti oluşturulmuştur. Sistemin temel modeli olarak, Türkçe dil yeteneği ve talimat takibi başarısı nedeniyle Gemma 3 12B tercih edilmiştir. Model, kaynak kısıtlı endüstriyel bilgisayarlarda çalışabilmesi için A100 GPU altyapısında, Unsloth kütüphanesi ve QLoRA (4-bit quantization) yöntemi kullanılarak ince ayar (fine-tuning) işlemine tabi tutulmuştur. LLM'lerin en büyük problemi olan halüsinasyon riskini minimize etmek amacıyla, RAG (Retrieval-Augmented Generation) mimarisi sisteme entegre edilmiştir. Teknik dokümanlar Multilingual-E5-Large embedding modeli ile vektörleştirilmiş ve hibrit arama yeteneği sunan Qdrant vektör veritabanında saklanmıştır. Sistem, yalnızca metin tabanlı bir asistan olmanın ötesinde, Çoklu Ajan (Multi-Agent) mimarisiyle tasarlanmıştır. Bu yapıda "RAG Ajanı" teknik dokümanları sorgularken, "Kestirimci Bakım Ajanı" üretim hattındaki sensör verilerini (akım, titreşim, ısı) analiz ederek olası arızaları bildrmektedir. Ayrıca gürültülü fabrika ortamlarında operatörlerin bilgiye ulaşımını kolaylaştırmak için OpenAI Whisper modeli ve RNN Noise Suppression gürültü engelleme algoritmaları kullanılarak yüksek doğruluklu sesli etkileşim (STT/TTS) sağlanması hedeflenmektedir. Elde edilen deneysel bulgular, geliştirilen sistemin uzman doğruluk oranını %37'den %69'a çıkardığını göstermektedir. Teknik terim kullanım başarısını ölçen BLEU skoru 18.2'den 66.5'e, anlamsal tutarlılığı ifade eden BERTScore ise 0.43'ten 0.79'a yükselmiştir. Sistem testlerinde belge geri getirme başarısı %99, en alakalı belgeyi bulma oranı ise %91 olarak ölçülmüştür. Ortalama 7-9 saniye cevap süresi ve %44 VRAM tasarrufu sağlayan bu çalışma, endüstriyel metal kesim süreçlerinde yapay zeka tabanlı asistanların verimliliği artırma ve bilgiye erişimi demokratikleştirme potansiyelini ortaya koymaktadır.

Anahtar Kelimeler: İnce Ayar Büyük Dil Modelleri, Bilgi Getirmeli Üretim Mimarisi, Akıllı Teknik Asistan, Ajan Tabanlı Yapay Zekâ, Testere Makinesi.

DEVELOPMENT OF A DATA-SECURITY-ORIENTED, AGENT-BASED INTELLIGENT ASSISTANT FOR METAL CUTTING MACHINES

ABSTRACT

Production efficiency in the metalworking industry fundamentally depends on operators' machine proficiency, rapid access to technical knowledge, and proactive intervention capabilities against potential failures. However, the dispersion of technical procedures and troubleshooting instructions across disconnected resources—combined with a shortage of experienced personnel—leads to costly issues such as incorrect parameter settings, reduced band and circular saw blade life, and unplanned machine downtime. This study presents an intelligent assistant system for metal-cutting machines, built on a Large Language Model (LLM) and designed to operate fully on-premise due to industrial data security requirements. A domain-specific dataset of 1,822 documents—consisting of technical service forms, user manuals, and machine logs—was constructed. Gemma 3 12B was selected as the core model thanks to its strong Turkish language understanding and instruction-following performance. To enable deployment on resource-constrained industrial PCs, the model was fine-tuned using the Unsloth library and QLoRA (4-bit quantization) technique on an A100 GPU infrastructure. To minimize hallucination risk—the most significant challenge of LLMs—a Retrieval-Augmented Generation (RAG) architecture was integrated. Technical documentation was embedded using the Multilingual-E5-Large model and stored in a Qdrant vector database providing hybrid search capabilities. Rather than functioning solely as a text-based assistant, the system is designed with a Multi-Agent architecture. In this setup, the "RAG Agent" retrieves relevant technical documentation while the "Predictive Maintenance Agent" analyzes production line sensor data (current, vibration, temperature) to report potential failures. Additionally, to improve operator accessibility in noisy factory environments, high-accuracy voice interaction (STT/TTS) is targeted through OpenAI Whisper and RNN-based noise suppression algorithms. Experimental results demonstrate that the proposed system improves expert-level accuracy from 37% to 69%. The BLEU score measuring technical term usage increased from 18.2 to 66.5, while semantic consistency measured by BERTScore improved from 0.43 to 0.79. System tests also revealed a 99% document retrieval success rate and 91% top-relevant document identification rate. With an average response time of 7–9 seconds and 44% VRAM savings, this study highlights the potential of AI-driven assistants to enhance efficiency and democratize access to knowledge in industrial metal-cutting operations.

Keywords: LLM Fine-Tuning, RAG Architecture, Intelligent Technical Assistant, Agentic AI, Sawing Machine

1. GİRİŞ

Endüstri 4.0 ve gelişmekte olan Endüstri 5.0 paradigmaları sürecinde, üretim verimliliği artık sadece otomasyonla değil, insan ve makine arasındaki iş birliğinin niteliğiyle de ölçülmektedir. Özellikle metal kesim sektörü gibi mikron düzeyinde hassasiyet gerektiren alanlarda, şerit ve daire testere makinelerinin verimli kullanımı operatör yetkinliği ile doğrudan ilişkilidir. Kesim hızı, baskı kuvveti ve şerit gerginliği gibi parametrelerin doğru ayarlanması, hem ürün kalitesini hem de sarf malzeme maliyetlerini belirleyen temel faktörlerdir. Ancak günümüzde üretim sahalarında yaşanan en büyük darboğazlardan biri, teknik prosedürlerin dağınık kaynaklarda (basılı kılavuzlar, PDF dosyaları, usta-çırak aktarımı) bulunması ve kalifiye personel eksikliğidir. Bu durum; hatalı parametre seçimlerine, kesici takım ömrünün kısalmasına ve en önemlisi plansız duruşlara (downtime) neden olarak işletmelere ciddi mali yükler getirmektedir.

Bu sorunların çözümünde, operatörlere gerçek zamanlı rehberlik edebilecek, kurumsal hafızayı dijitalleştirerek erişilebilir kılan yapay zeka tabanlı akıllı asistan sistemleri kritik bir rol oynamaktadır. Literatür incelendiğinde, bu alandaki çalışmaların genellikle üç ana eksende yoğunlaştığı görülmektedir: Operatör yönlendirme amaçlı Büyük Dil Modelleri (LLM), gürültülü ortamlarda sesli etkileşim teknolojileri ve otonom karar destek sağlayan ajan mimarileri.

Birinci eksen olan operatör yönlendirme sistemleri kapsamında, LLM'lerin endüstriyel bakım süreçlerine entegrasyonu üzerine çeşitli çalışmalar mevcuttur. (Kiangala ve Wang, 2024), Endüstri 5.0 bağlamında yaptıkları deneysel bir çalışmada, fabrika arıza giderme süreçlerini iyileştirmek için hibrit bir üretken yapay zeka chatbot arayüzü geliştirmiş ve bu sistemin Ortalama Onarım Süresini (MTTR) önemli ölçüde düşürdüğünü raporlamışlardır. Benzer şekilde, makinelerden alınan telemetri verilerinin LLM ile analiz edilerek kestirimci bakım süreçlerinde operatörlere doğal dilde geri bildirim sağlanmasının, bakım maliyetlerini düşürdüğü ortaya konulmuştur (Predictive Maintenance for Industrial Machinery Using LLM, 2025). Ancak bu çalışmaların çoğu, veri güvenliği (cloud dependency) ve halüsinasyon (yanlış bilgi üretme) riski nedeniyle endüstriyel adaptasyonda zorluklar yaşamaktadır.

İkinci eksen, endüstriyel ortamlarda sesli etkileşimdir. Operatörlerin ellerini kullanmadan makineye müdahale edebilmesi (hands-free), iş güvenliği ve operasyonel hız açısından elzemdir. Fabrika ortamlarındaki yüksek arka plan gürültüsü (metal kesim sesi, motor gürültüsü vb.), standart ses tanıma sistemlerinin performansını düşürmektedir. Bu çalışmada, OpenAI Whisper modeli ve RNN Noise Suppression algoritmaları kullanılarak, gürültülü metal kesim atölyelerinde dahi yüksek doğrulukla çalışan Türkçe bir sesli asistan mimarisi hedeflenmiştir.

Üçüncü ve en güncel eksen ise Çoklu Ajan (Multi-Agent) ve multimodal sistemlerdir. Tek başına bir dil modelinin tüm sensör verilerini, teknik dokümanları ve bakım geçmişini işlemesi mümkün olmadığından, görev paylaşımı yapan ajan mimarileri önem kazanmıştır. (Palma ve arkadaşları, 2025) tarafından deri endüstrisindeki kompresörler üzerinde yapılan bir çalışmada, çok modlu anomali tespiti için LLM tabanlı ajanların kullanıldığı ve karmaşık sensör verilerinin bu sayede anlamlandırıldığı görülmüştür. Ayrıca, Bilgi Grafikleri (Knowledge Graph) ile LLM füzyonunu öneren çalışmalar (Hoang vd., 2025; Alsaif vd., 2024), üretim planlamasında modelin halüsinasyon riskini azaltarak daha güvenilir teknik çıktılar ürettiğini göstermektedir.

Mevcut literatürdeki çalışmalar değerli olmakla birlikte, bu üç ekseni (LLM rehberliği, gürültüye dayanıklı sesli etkileşim ve çoklu ajan yapısı) tek bir sistemde birleştiren ve veri

güvenliği nedeniyle tamamen yerel ağda (on-premise) çalışan özelleşmiş çözümler sınırlıdır. Bu çalışma, metal kesim makineleri için RAG (Retrieval-Augmented Generation) destekli, Gemma 3 tabanlı ve çoklu ajan mimarisine sahip bir akıllı asistan sistemini sunarak literatürdeki bu boşluğu doldurmayı amaçlamaktadır.

2. GELİŞME

Bu bölümde, geliştirilen akıllı asistan sisteminin mimarisi, kullanılan veri setleri, ince ayar yöntemleri ve elde edilen deneysel bulgular detaylandırılmaktadır. Sistem; Veri Katmanı, LLM Çekirdeği, RAG Mimarisi ve Çoklu Ajan Yapısı olmak üzere dört ana modülden oluşmaktadır.

2.1. Veri Toplama ve İşleme Süreçleri

Yapay zeka modellerinin endüstriyel alanda başarılı olabilmesinin temel şartı, alan (domain) uzmanlığına sahip verilerle eğitilmesidir. Proje kapsamında, genel geçer internet verileri yerine gerçek saha verileri kullanılmıştır. Veri kaynakları şu başlıklardan oluşmaktadır:

Teknik Servis Formları: Geçmiş arızaların nedenleri ve uygulanan çözüm adımlarını içeren raporlar.

Kullanım ve Bakım Kılavuzları: Makine üreticilerinin sağladığı teknik spesifikasyonlar ve prosedürler.

Operatör Geri Bildirimleri: Sahadan toplanan, yapısal olmayan (unstructured) notlar.

Ham veriler üzerinde öncelikle Kişisel Verilerin Korunması Kanunu (KVKK) kapsamında anonimleştirme işlemi uygulanmıştır. Ardından metin temizleme, "stopwords" temizliği ve makine modeline özgü jargonun korunması sağlanmıştır. İşleme süreci sonunda servis formlarından 1.304 adet, kılavuzlardan ise 1.000 adet soru-cevap çifti (instruction-input-output formatında) üretilmiştir. Veri temizleme ve genelleştirme işlemleri sonrası toplam 1.822 adet yüksek nitelikli veri seti elde edilmiştir. Bu veri seti, modelin "Metal Kesim Asistanı" kimliğini kazanması için temel eğitim materyalini oluşturmuştur.

2.2. LLM Katmanı ve QLoRA ile İnce Ayar

Sistemin temel zeka katmanında, Google tarafından geliştirilen açık kaynaklı Gemma 3 12B modeli tercih edilmiştir. Bu modelin seçilmesindeki temel nedenler; Türkçe dil yeteneğinin yüksek olması, talimat takip (instruction following) başarısı ve 12 milyar parametre boyutuyla performans/kaynak dengesini sağlamasıdır.

Endüstriyel bilgisayarların donanım kısıtları göz önüne alındığında, modelin tam parametre (full fine-tuning) ile eğitilmesi hem maliyetli hem de donanım açısından zorlayıcıdır. Bu nedenle, projede Unsloth kütüphanesi ve QLoRA (Quantized Low-Rank Adaptation) metodu kullanılmıştır. QLoRA, modelin tüm ağırlıklarını güncellemek yerine, dondurulmuş 4-bit ağırlıklar üzerinden düşük rütbeli adaptörleri eğitmektedir. Eğitim süreci A100 GPU altyapısında gerçekleştirilmiştir. Bu yöntem sayesinde VRAM kullanımında %44 oranında tasarruf sağlanmış, modelin çıkarım (inference) hızı artırılmış ve donanım maliyetleri minimize edilmiştir.

2.3. RAG (Retrieval-Augmented Generation) Mimarisi

Büyük dil modellerinin endüstriyel kullanımındaki en büyük risk "halüsinasyon" olarak adlandırılan, modelin bilmediği konularda gerçeğe aykırı bilgi uydurmasıdır. Bir metal kesim makinesinde yanlış hidrolik basınç değeri önermek, ciddi iş kazalarına yol açabilir. Bu riski ortadan kaldırmak için sisteme RAG mimarisi entegre edilmiştir.

RAG akışı şu şekilde çalışmaktadır:

Vektörleştirme (Embedding): Teknik dokümanlar, paragraflar halinde bölünerek Multilingual-E5-Large modeli ile sayısal vektörlere dönüştürülmüştür. Bu model, Türkçe semantik (anlamsal) ilişkileri kurmada yüksek başarı göstermektedir.

Vektör Veritabanı: Elde edilen vektörler, Qdrant veritabanında saklanmıştır. Qdrant'ın seçilme nedeni, hibrit arama (dense + sparse vector search) desteği sunması ve milisaniye düzeyinde sorgu yapabilmesidir.

Sorgulama: Kullanıcı bir soru sorduğunda, sistem önce Qdrant üzerinden en alakalı teknik dokümanı bulmakta ("Retrieval"), ardından bu bilgiyi LLM'e bağlam (context) olarak sunarak ("Augmented") cevabı üretmektedir ("Generation").

2.4. Çoklu Ajan (Multi-Agent) Sistemi

Modern endüstriyel problemler, tek bir modelin çözemeyeceği kadar karmaşıktır. Bu nedenle sistem, özelleşmiş görevleri olan ajanların iş birliği (orchestration) ile çalıştığı bir yapıda tasarlanmıştır:

RAG Ajanı: Kullanıcının teknik bilgi veya prosedür gerektiren sorularını analiz eder. get_documents_from_qdrant aracını kullanarak teknik belgeleri getirir ve yanıtı formüle eder.

Kestirimci Bakım (Predictive Maintenance) Ajanı: Üretim hattındaki PLC ve sensörlerden gelen verilere (motor akımı, titreşim seviyesi, kesme sıvısı sıcaklığı vb.) get_sensor_data aracı ile erişir. Tanımlanan eşik değerlerin dışına çıkan anormallikleri tespit eder ve arıza henüz oluşmadan operatörü uyarır (Örn: "Şerit testere motor akımı normalin %15 üzerinde, rulman kontrolü önerilir.").

2.5. Gürültü Engelleyici Sesli Etkileşim

Metal kesim atölyeleri, desibel seviyesinin yüksek olduğu ortamlardır. Operatörün klavye kullanmadan asistanla iletişim kurabilmesi için gelişmiş bir ses işleme boru hattı (pipeline) kurulmuştur:

STT (Speech-to-Text): OpenAI Whisper modeli kullanılarak operatörün konuşması metne çevrilir.

Gürültü Bastırma: Whisper öncesinde, arka plandaki metal kesme ve fan seslerini izole etmek için RNN Noise Suppression algoritması entegre edilmiştir.

TTS (Text-to-Speech): Asistanın ürettiği cevaplar, doğal ve anlaşılır bir ses tonuyla operatöre sesli olarak iletilir.

2.6. Deneysel Bulgular ve Performans Analizi

Geliştirilen sistemin performansı; doğruluk oranı, dilsel tutarlılık ve sistem yanıt süreleri üzerinden değerlendirilmiştir.

Uzman Doğruluk Oranı: Temel modelin (ham Gemma 3) sektörel sorulara doğru cevap verme oranı %37 iken, 1.822 adetlik veri seti ile yapılan ince ayar (fine-tuning) ve RAG entegrasyonu sonrası bu oran %69'a yükselmiştir. Bu artış, modelin sektörel terminolojiye hakimiyetini kanıtlamaktadır.

Dilsel Metrikler (BLEU ve BERTScore):

BLEU Skoru: Modelin teknik terimleri doğru kullanma başarısını ölçen skor, 18.2’den 66.5’e yükselmiştir.

BERTScore: Cevapların anlamsal tutarlılığını ifade eden skor, 0.43'ten 0.79'a çıkmıştır. Bu durum, asistanın sadece kelime eşleşmesi yapmadığını, sorunun bağlamını anladığını göstermektedir.

Sistem Performansı: Sistem testlerinde, Qdrant üzerinden belge geri getirme başarısı (Recall) %99, en alakalı belgeyi ilk sırada bulma oranı (Precision@1) ise %91 olarak ölçülmüştür. Ortalama cevap süresi, RAG sorgusu dahil olmak üzere 7-9 saniye aralığında gerçekleşmiş olup, operasyonel akışı aksatmayacak hızdadır.

Senaryo Bazlı Test: Gerçek saha senaryolarında yapılan testlerde, örneğin bir operatörün "Makine neden yamuk kesiyor?" sorusuna sistem şu şekilde yanıt üretmiştir: "Yamuk kesim problemi; düşük şerit germe basıncı (< 150 bar) veya elmas kol hizasızlığından kaynaklanabilir. Lütfen önce manometreden basıncı kontrol edin, ardından mengene boşluklarını kumpas ile ölçün." Bu yanıt, modelin RAG katmanı sayesinde genel geçer öneriler yerine, parametrik değerler içeren teknik bir rehberlik sağladığını göstermektedir.

3. SONUÇ

Bu çalışmada, metal kesim makineleri için geliştirilen, yerli mühendislik imkanlarıyla optimize edilmiş bir akıllı asistan çözümü sunulmuştur. Çalışmanın en önemli çıktısı, sınırlı veri setine (1.822 adet) rağmen, doğru model seçimi (Gemma 3) ve modern ince ayar teknikleri (QLoRA) ile yüksek performanslı bir endüstriyel asistanın geliştirilebileceğinin gösterilmesidir.

Sistemin RAG mimarisi ile desteklenmesi, LLM'lerin en büyük zaafı olan halüsinasyon problemini minimize etmiş ve operatörlere teknik dokümanlara dayalı güvenilir bilgi sunulmasını sağlamıştır. Ayrıca, verilerin bulut yerine tamamen yerel ağda (on-premise) işlenmesi, stratejik öneme sahip üretim verilerinin ve teknik "know-how"ın işletme içinde kalmasını sağlayarak veri güvenliği standartlarını karşılamıştır. Çoklu ajan yapısı ise sistemi pasif bir bilgi bankası olmaktan çıkarıp, sensör verilerini yorumlayabilen proaktif bir bakım asistanına dönüştürmüştür.

Gelecek çalışmalarda; veri setinin farklı arıza senaryoları ve görsel verilerle (arıza fotoğrafları) zenginleştirilmesi, modelin Multimodal (görüntü işleyebilen) yeteneklerle donatılması ve farklı marka/model metal işleme makinelerine adapte edilebilecek esnek bir yapıya kavuşturulması hedeflenmektedir. Bu sonuçlar, yapay zeka tabanlı asistanların Endüstri 4.0 sürecinde verimliliği artırma ve bilgiye erişimi demokratikleştirme potansiyelini açıkça ortaya koymaktadır.

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MANAGESQL: YEREL BÜYÜK DİL MODELLERİYLE MES TABANLI DİNAMİK SORGU ÜRETİMİ VE VERİ TABANI PERFORMANS İZLEME SİSTEMİ

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ÖZET

Endüstri 4.0 ve dijital dönüşüm süreçlerinde, Üretim Yönetim Sistemleri (MES) tarafından üretilen verilerin anlamlandırılması kritik bir önem taşımaktadır. Ancak, karmaşık veritabanı şemaları ve SQL (Structured Query Language) uzmanlığı gereksinimi, karar vericilerin verilere anlık erişimini kısıtlamaktadır. Bu çalışma, CoralReef MES sistemi üzerine entegre edilen, yerel ağda (on-premise) çalışan ve veri gizliliğini esas alan ManageSQL adlı yapay zeka destekli bir sistemi sunmaktadır. Proje kapsamında, Qwen 2.5 Coder ve Gemma 3 gibi Büyük Dil Modelleri (LLM), kurumsal veritabanı yapısına özgü olarak ince ayar (fine-tuning) ve İnsan Geri Bildirimli Pekiştirmeli Öğrenme (RLHF) yöntemleriyle eğitilmiştir. Sistemin başarısını artırmak amacıyla RAG (Retrieval-Augmented Generation) mimarisi kullanılmış; teknik terimler, tablo ilişkileri ve geçmiş sorgu örnekleri Qdrant vektör veri tabanında hibrit arama yöntemleriyle indekslenmiştir. Ayrıca sistem, yalnızca sorgu üretmekle kalmayıp, veri tabanı üzerindeki CPU kullanımı, sorgu süreleri ve indeks verimliliği gibi performans metriklerini izleyen entegre bir dashboard sunmaktadır. Elde edilen ön deneysel bulgular, Qwen 2.5 Coder 7B modelinin uzman doğruluk oranında %76.7 başarı yakalayarak, diğer modellere kıyasla daha istikrarlı bir performans sergilediğini göstermektedir.

Anahtar Kelimeler: Text-to-SQL, Büyük Dil Modelleri, İnce Ayar ,İnsan geri bildirimiyle yönlendirilen pekiştirmeli öğrenme (RLHF), MES (Manufacturing Execution System)

MANAGESQL: DYNAMIC SQL QUERY GENERATION AND DATABASE PERFORMANCE MONITORING IN MES SYSTEMS USING LOCAL LARGE LANGUAGE MODELS

ABSTRACT

In Industry 4.0 and digital transformation processes, deriving actionable insights from data generated by Manufacturing Execution Systems (MES) is of critical importance. However, complex database schemas and the requirement for SQL (Structured Query Language) expertise limit real-time data accessibility for decision-makers. This study presents ManageSQL, an on-premise, privacy-preserving, AI-powered system integrated into the CoralReef MES platform. As part of the project, Large Language Models (LLMs) such as Qwen 2.5 Coder and Gemma 3 were fine-tuned using Reinforcement Learning from Human Feedback (RLHF) and domain-specific training aligned with the corporate database structure. To enhance system performance, a Retrieval-Augmented Generation (RAG) architecture was employed. Technical terminology, table relationships, and historical SQL query examples were indexed using hybrid search techniques within a Qdrant vector database. In addition to generating SQL queries, the system includes a performance monitoring dashboard that tracks metrics such as CPU utilization, query execution times, and index efficiency within the database. Preliminary experimental results indicate that the Qwen 2.5 Coder 7B model achieved 76.7% expert-level accuracy, demonstrating more stable performance compared to alternative models.

Keywords: Text-to-SQL, Large Language Models (LLM), Fine-Tuning, Reinforcement Learning from Human Feedback (RLHF), MES (Manufacturing Execution System)

1. GİRİŞ

Endüstri 4.0 sürecinde veriye dayalı karar alma mekanizmaları, üretim işletmelerinin rekabet gücünü belirleyen en kritik unsurlardan biri haline gelmiştir. İlişkisel veri tabanlarında saklanan büyük hacimli üretim verilerine (MES, ERP, BPM) erişim, geleneksel yöntemlerle SQL (Structured Query Language) uzmanlığı gerektirmektedir. Ancak üretim sahasındaki yöneticilerin veya operasyonel personelin teknik jargon kullanmadan, doğal dilde ("Bu ay en çok duruş yapan makineleri listele" gibi) veri talep etme ihtiyacı giderek artmaktadır. Literatürde "Text-to-SQL" olarak adlandırılan bu problem, Büyük Dil Modellerinin (LLM) gelişimiyle yeni bir boyut kazanmış olsa da, endüstriyel uygulamalarda veri güvenliği, halüsinasyon riski ve karmaşık şema yapılarının yönetimi gibi temel zorluklar devam etmektedir. Literatür incelendiğinde, bu alandaki güncel çalışmaların genellikle üç ana eksende yoğunlaştığı görülmektedir: LLM tabanlı üretim tekniklerinin (Prompting vs. Fine-tuning) karşılaştırılması, RAG (Retrieval-Augmented Generation) destekli şema eşleştirme ve çoklu ajan (Multi-Agent) tabanlı doğrulama mekanizmaları.

Birinci eksen olan LLM tabanlı üretim teknikleri kapsamında, GPT-4 gibi kapalı kaynak modellerin yüksek başarım gösterdiği bilinmekle birlikte, veri gizliliği ve maliyet endişeleri araştırmacıları açık kaynaklı modellere yöneltmektedir. Li ve arkadaşları (2024), "CodeS" gibi açık kaynaklı modellerin, Text-to-SQL görevi için özel olarak tasarlandığında ve aşamalı ön eğitimden geçirildiğinde, çok daha küçük parametre boyutlarıyla (1B-15B) rekabetçi sonuçlar üretebildiğini göstermiştir. Ayrıca, istem mühendisliği (prompt engineering) ve ince ayar (fine-tuning) yaklaşımlarının karşılaştırıldığı çalışmalarda, ince ayarın özellikle alan (domain) adaptasyonu gerektiren durumlarda potansiyel kazanımları artırdığı ancak yüksek hesaplama maliyeti getirdiği vurgulanmaktadır. Nan ve arkadaşları (2023) ise sistematik prompt tasarımı ve sözdizimi tabanlı örnek seçimi ile LLM'lerin yapılandırılmış veri kaynaklarından bilgi çıkarma yeteneklerinin artırılabileceğini kanıtlamıştır.

İkinci eksen, LLM'lerin en büyük problemi olan halüsinasyon riskini azaltmaya yönelik RAG ve şema bağlantısı (schema linking) çalışmalarıdır. Gurawa ve Dharmik (2025), RAG sistemlerinde içeriği zenginleştirmenin her zaman başarı getirmediğini, aksine gürültü (noise) ekleyerek modelin performansını düşürebileceğini belirtmiş; doküman boyutu ve kalitesi arasında hassas bir denge kurulması gerektiğini savunmuştur. Karmaşık veritabanı şemalarının yönetilmesi konusunda ise Yuan ve arkadaşları (2025), "KaSLA" adını verdikleri tak-çanta optimizasyonuna dayalı bir şema eşleme yöntemi önermiş ve bu yöntemin gereksiz öğeleri elediğini ortaya koymuştur. Benzer şekilde Cao ve arkadaşları (2024), çift yönlü şema bağlantısı ve budama yöntemleriyle girdi sütun sayısını %83 oranında azaltarak GPT-4o tabanlı sistemlerde SOTA (State-of-the-Art) performans elde etmiştir.

Üçüncü ve en güncel eksen ise sorgu karmaşıklığını yönetmek için geliştirilen parçalama (decomposition) ve ajan tabanlı mimarilerdir. Tek adımlı düşünce zinciri (Chain-of-Thought) yaklaşımının karmaşık görevlerde yetersiz kalması üzerine, Xie ve arkadaşları (2024) iş akışı paradigmasına dayalı bir yöntem önererek problemi alt parçalara ayırmış ve Spider test setinde yeni bir SOTA elde etmiştir. FATO-SQL gibi çerçeveler, RAG, prompt mühendisliği ve çoklu LLM çağrılarını birleştirerek karmaşık SQL sorgularında %94 doğruluk oranına ulaşmıştır. Ayrıca, SQL-o1 gibi ajan tabanlı mimariler, Monte Carlo Ağacı Araması (MCTS) kullanarak çözüm uzayını dinamik olarak keşfetmekte ve özellikle karmaşık veri setlerinde (BIRD) GPT-4 tabanlı modelleri geride bırakmaktadır.

Mevcut literatürdeki bu gelişmeler, Text-to-SQL alanında önemli bir olgunluğa işaret etse de, çoğu çalışma ya genel geçer veri setleri (Spider, BIRD) üzerinde kalmakta ya da veri güvenliği nedeniyle endüstriyel MES sistemlerine tam entegre olamamaktadır. Ayrıca, üretilen SQL'in

veritabanı performansına etkisini (CPU yükü, indeks kullanımı vb.) analiz eden bütünleşik bir yaklaşım eksikliği dikkat çekmektedir. Bu çalışma, CoralReef MES sistemi için geliştirilen ManageSQL projesi ile; (1) yerel ağda çalışan ve veri güvenliğini sağlayan ince ayarlı bir LLM (Qwen 2.5/Gemma 3), (2) kurumsal şema yapısını öğrenen hibrit bir RAG mimarisi ve (3) veritabanı performansını izleyen bir analiz dashboard'unu birleştirerek literatürdeki bu boşluğu doldurmayı amaçlamaktadır.

2. GELİŞME

ManageSQL sistemi; veri hazırlama, model eğitimi, RAG mimarisi ve kullanıcı arayüzü olmak üzere dört temel katman üzerine inşa edilmiştir. Bu bölümde, sistemin teknik mimarisi, kullanılan veri setleri ve uygulanan ince ayar yöntemleri detaylandırılmaktadır.

2.1. Sistem Mimarisi ve Bileşenler

Sistem, kullanıcıdan gelen doğal dil sorgusunu alarak işleyen ve güvenli bir SQL çıktısı üreten çok katmanlı bir yapıya sahiptir.

- **Doğal Dil Girdi Katmanı:** Kullanıcıların MES ve BPM süreçlerine dair sorularını ilettiği web tabanlı arayüzdür.
- **Embedding ve Retrieval Katmanı:** Sorgular, multilingual-e5-large modeli ile vektörleştirilmekte ve Qdrant vektör veritabanı üzerinde anlamsal arama yapılmaktadır.
- **LLM Çekirdeği:** Sisteme entegre edilen yerel LLM (Gemma 3 veya Qwen 2.5), getirilen bağlam bilgisi (RAG context) ile birlikte sorguyu işleyerek SQL üretmektedir.
- **Doğrulama Katmanı:** Üretilen SQL, zararlı komutlara (DROP, DELETE) karşı analiz edilmekte ve yalnızca okuma (SELECT) yetkisiyle sınırlandırılmaktadır.
- **Performans Analiz Dashboardu:** Veritabanı üzerindeki yük, çalışma süresi, CPU kullanımı ve yavaş sorgular görselleştirilerek kullanıcıya sunulmaktadır.

2.2. Veri Toplama ve İşleme Süreçleri

Modelin başarısı, kullanılan eğitim verisinin kalitesine ve alan (domain) uygunluğuna doğrudan bağlıdır. Proje kapsamında iki ana veri kaynağı kullanılmıştır:

1. **Kurumsal Veri Seti:** İletişim Yazılım'ın MES ve BPM projelerinden elde edilen gerçek senaryolar. Toplam 2.220 adet doğal dil ve SQL eşleşmesi, 500 adet tablo ve ilişki yapısı etiketlenmiştir.
2. **Açık Kaynak Veri Seti (TurSpyder):** Modelin Türkçe dil yeteneğini ve genel SQL mantığını güçlendirmek için 8.000 adetlik NL-SQL çifti kullanılmıştır.

Veriler, "instruction" (talimat), "context" (veritabanı şeması) ve "response" (hedeflenen SQL) formatında JSON yapılarına dönüştürülmüştür. Örneğin, "Çalışan bilgilerini getir" sorgusu için ilgili tablo (Employee), bağlı olduğu üst tablo (Yonetici) ve modül bilgisi (Fabrika) bağlam olarak modele sunulmaktadır.

2.3. Model Seçimi ve İnce Ayar (Fine-Tuning) Yöntemleri

Projede, düşük donanım kaynağı ile yüksek performans hedeflendiği için "Qwen 2.5 Coder 7B" ve "Gemma 3 12B" modelleri üzerinde karşılaştırmalı çalışmalar yapılmıştır. Eğitim sürecinde iki aşamalı bir yaklaşım benimsenmiştir:

1. Denetimli İnce Ayar (Supervised Fine-Tuning - SFT): Model, hazırlanan veri setleri ile tablo seçimi, JOIN yapılarının kurgulanması ve tarih filtreleri (WHERE koşulları) konusunda eğitilmiştir. Donanım kısıtlarını aşmak için A100 GPU üzerinde **Unsloth** kütüphanesi ve

QLoRA (4-bit quantization) teknolojisi kullanılmıştır. Bu yöntem, VRAM ihtiyacını azaltırken eğitim hızını artırmıştır.

2. Doğrudan Tercih Optimizasyonu (Direct Preference Optimization - DPO): Modelin ürettiği SQL çıktılarının kalitesini artırmak için İnsan Geri Bildirimli Pekiştirmeli Öğrenme (RLHF) prensibine dayalı DPO uygulanmıştır. Aynı sorgu için modelin ürettiği birden fazla çıktı uzmanlar tarafından "Tercih Edilen" (Preferred) ve "Tercih Edilmeyen" (Non-preferred) olarak etiketlenmiştir. Bu sayede model; uydurma kolon isimleri kullanma veya gereksiz JOIN yapma gibi hatalardan kaçınmayı öğrenmiştir.

2.4. RAG Mimarisi ve Vektör Veritabanı Entegrasyonu

Büyük dil modellerinin en büyük zafiyeti olan halüsinasyon (yanlış bilgi üretme) riskini minimize etmek için RAG mimarisi sisteme entegre edilmiştir.

- **Retrieval (Geri Getirim):** Kullanıcı sorgusu geldiğinde, Qdrant veritabanı üzerinde **Hibrit Arama** (Hybrid Search) yapılmaktadır. Bu yaklaşımda, semantik anlamı yakalamak için "Dense Embedding" (Multilingual-E5-Large) ve teknik terim eşleşmesi için "BM25" (Lexical Search) algoritmaları birlikte kullanılarak en alakalı şema bilgisi çekilmektedir.
- **Augmentation (Zenginleştirme):** Veritabanından çekilen en alakalı tablo şemaları ve örnek SQL kalıbı, LLM'e giden "prompt" içerisine eklenerek modelin doğru bağlamda çalışması sağlanmaktadır.

2.5. Veritabanı Performans İzleme

ManageSQL, sadece sorgu üreten pasif bir sistem değil, aynı zamanda veritabanı sağlığını izleyen aktif bir araçtır. Geliştirilen dashboard modülü, bağlı veritabanı üzerinde periyodik olarak performans analiz sorguları çalıştırmaktadır. Toplam tablo sayısı, bellek kullanımı, trigger sayıları ve anlık CPU yükü gibi kritik metrikler görselleştirilerek veritabanı yöneticilerine (DBA) karar destek imkanı sunulmaktadır.

2.6. Bulgular ve Deneysel Sonuçlar

Geliştirilen sistemin performansı, henüz geliştirme aşamasında olmasına rağmen umut verici sonuçlar vermiştir. Yapılan testlerde "Uzman Doğruluk Oranı" (Expert Accuracy) ve "Tam Eşleşme Skoru" (Exact Match Score) metrikleri kullanılmıştır.

- **Gemma 3 12B:** Uzman doğruluk oranı **%36.7**, Tam Eşleşme Skoru **0.32** olarak ölçülmüştür.
- **Qwen 2.5 Coder 7B:** Uzman doğruluk oranı **%56.7**, Tam Eşleşme Skoru **0.68** seviyesine ulaşmıştır.

Qwen modelinin, özellikle kodlama ve SQL sentaksına yönelik özelleşmiş yapısı sayesinde, Türkçe komutları SQL mantığına dönüştürmede Gemma 3'e göre daha başarılı olduğu gözlemlenmiştir. DPO ve RAG entegrasyonunun tam olarak tamamlanmasıyla bu oranların daha da artması beklenmektedir.

3. SONUÇ

Bu çalışmada, üretim sektörünün veri analitiği ihtiyaçlarına yönelik, yerli ve milli imkanlarla geliştirilen ManageSQL sistemi tanıtılmıştır. Bulut tabanlı sistemlerin güvenlik risklerini ortadan kaldıran bu yerel (on-premise) çözüm, Qwen 2.5 Coder modeli üzerine uygulanan SFT ve DPO teknikleri ile kurumsal veritabanı yapısını öğrenme yeteneği kazanmıştır.

Çalışmanın temel çıktıları şunlardır:

1. **Veri Güvenliği:** Tüm süreç yerel ağda gerçekleştiği için hassas üretim verileri korunmuştur.

2. **Yüksek Başarım:** Qwen 2.5 Coder modeli, kısıtlı eğitim verisine rağmen %76.7 doğruluk oranına ulaşarak endüstriyel uygulanabilirliğini kanıtlamıştır.

3. **Hibrit RAG Yapısı:** Qdrant ve BM25 entegrasyonu sayesinde, modelin halüsinasyon oranı düşürülmüş ve doğru tablo seçimi garanti altına alınmıştır.

4. **Bütünleşik Çözüm:** SQL üretimi ile veritabanı performans izleme süreçleri tek bir platformda birleştirilmiştir.

Gelecek çalışmalarda, eğitim veri setinin genişletilmesi, çoklu ajan (multi-agent) yapılarının entegrasyonu ve modelin kendi kendini düzeltebilen (self-correction) bir yapıya kavuşturulması hedeflenmektedir. Bu proje, yapay zekanın üretim yönetim sistemlerine entegrasyonunda önemli bir adım teşkil etmektedir.

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JACOBSTHAL AND JACOBSTHAL-LUCAS DIFFERENTIAL EQUATIONS

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ABSTRACT

The hypergeometric function provides a general form for numerous integrals, differential equations, and special functions. Hypergeometric equation is a second order differential equation, the general solution of which are represented as hypergeometric functions. Since many physics problems (quantum and potential theory) can be reduced to this equation form, it is an important tool for applied sciences. Jacopsthal polynomials are a special family of polynomials closely related to combinatorics and number theory, despite having received little attention in the literature. The purpose of this research is to construct the differential equations for the Jacobsthal and Jacobsthal-Lucas polynomials. Then using the solutions of these equations, the hypergeometric forms of the Jacobsthal and Jacobsthal-Lucas polynomials are found. Finally, some relations between these polynomials and the other well-known functions will be examined.

Keywords: Jacobsthal polynomials, Jacobsthal-Lucas polynomials, hypergeometric equation, hypergeometric function.

MSC 2010 No.: 11B83, 33C05

1. INTRODUCTION

The theory of special functions is frequently used in certain fields such as approximation theory, numerical integration, the solution of differential equations using spectral methods, signal processing and data compression, statistics and probability theory, and physical problems. Jacobsthal polynomials also appear in various fields including number theory, coding theory, approximation theory, orthogonality connections, physics and engineering, computer science and algorithms. Some important studies involving Jacobsthal polynomials are given in [1-10].

Ernst Jacobsthal, a German mathematician, explored Jacobsthal numbers and polynomials in the 20th century. Jacobsthal polynomials $J_n(x)$ expressed by

$$J_{n+1}(x) = J_n(x) + 2x\,J_{n-1}(x), n \geq 1, \quad (1)$$

where $J_0(x) = 1, J_1(x) = 1$. These polynomials have the following differential recurrence relations

$$2(n-1)\,J_n(x) = J'_{n+1}(x) + 4x\,J'_n(x), \quad (2)$$

$$2n\,J_{n-1}(x) = 2\,J'_{n+1}(x) - J'_n(x). \quad (3)$$

Jacobsthal-Lucas polynomials $j_n(x)$ defined by

$$j_{n+1}(x) = j_n(x) + 2x\,j_{n-1}(x), n \geq 1, \quad (4)$$

where $j_0(x) = 2, j_1(x) = 1$. These polynomials yield the following differential recurrence relations

$$4n\,j_n(x) - 2(n-1)j_{n-1}(x) = j'_{n+1}(x) + 8x\,j'_n(x) - 2x\,j'_{n-1}(x), \quad (5)$$

$$(1+8x)j'_n(x) = 4n\,j_n(x) - 2n\,j_{n-1}(x). \quad (6)$$

On the other hand, the form of the hypergeometric differential equation

$$x(1-x)y'' + [c-(a+b+1)x]y'' - aby = 0, \quad (7)$$

where 0, 1, and ∞ are three regular singular points. Any second-order ODE with up to three regular singular points can be converted into a hypergeometric differential equation with appropriate variables. Many of the most fascinating special functions in applied sciences can be found in the solutions of hypergeometric differential equations [11, 12, 13].

A hypergeometric differential equation's solution is

$$y(x) = AF(a,b;c;x) + Bx^{1-c}\,F(a-c+1, b-c+1; 2-c,;x). \quad (8)$$

Here, $F(a,b;c;x)$ is known to as the hypergeometric function, which is defined as

$$F(a,b;c;x) = \sum_{l=0}^{\infty} \frac{(a)_l\,(b)_l}{(c)_l}\frac{x^l}{l!}, \quad (9)$$

where the Pochhammer symbol is denoted by $(m)_l$ which is defined by

$$(m)_l = \frac{\Gamma(m+l)}{\Gamma(m)} (m \in \boldsymbol{C}\backslash\boldsymbol{Z_0^-})$$

$$= \begin{cases} 1, & if\ \ l = 0; m \in \boldsymbol{C}\backslash\{0\} \\ m(m+1)\ldots(m+l-1), & if\ \ l = n \in \boldsymbol{N}; m \in \boldsymbol{C} \end{cases}$$

where $\boldsymbol{Z_0^-} = \{0, -1, -2, \ldots\}$ and $\Gamma(m)$ is the gamma function.

In this study, we construct a differential equation for the Jacobsthal polynomials and found their hypergeometric form. In a similar manner, we derive a differential equation from which we use the polynomial solution to determine the hypergeometric form of the Jacobsthal-Lucas polynomials. Then, we express the Jacobsthal and Jacobsthal-Lucas polynomials in terms of Olver's hypergeometric functions. Finally, we obtain some relations between these polynomials and certain functions and orthogonal polynomials, such as Legendre and Jacobi.

2. JACOBSTHAL DIFFERENTIAL EQUATIONS

The hypergeometric form for the Jacobsthal polynomials and a differential equation named as the Jacobsthal differential equation are derived in this section. The Jacobsthal polynomials and other known functions or polynomials are then related in specific ways.

Theorem 2.1. The following differential equation is satisfied by the Jacobsthal polynomials $J_n(x)$:

$$x(1+8x)y'' - [n-1+4(2n-5)x]y' + 2(n-1)(n-2)y = 0. \tag{10}$$

Proof: The desired solution is obtained by using the recurrence relations (2) and (3) along with certain computations.

Theorem 2.2. The following equality is the expression of Jacobsthal polynomials $J_n(x)$ in terms of hypergeometric functions:

$$J_n(x) = \frac{(2)_{n-1}}{(n-1)!\ 2^{n-1}} F\left(\frac{1-n}{2}, \frac{2-n}{2}; \frac{3}{2}; 1+8x\right). \tag{11}$$

Proof: Since the Jacobsthal polynomials $J_n(x)$ are the solution of (10), we can write

$$x(1+8x)\,J_n'' - [n-1+4(2n-5)x]\,J_n' + 2(n-1)(n-2)\,J_n = 0.$$

In this case, applying the mapping $u = 1+8x$, we have

$$u(1-u)\frac{d^2J_n}{du^2} + \left(\frac{3}{2} - \left(\frac{5-2n}{2}\right)u\right)\frac{dJ_n}{du} - \frac{(n-1)(n-2)}{4}J_n = 0.$$

The following constants are obtained by comparing the last equation with (7):

$$c = \frac{3}{2}, a = \frac{1-n}{2}, b = \frac{2-n}{2}.$$

The general solution of (10) is

$$J_n(u) = AF\left(\frac{1-n}{2}, \frac{2-n}{2}; \frac{3}{2}; u\right) + Bu^{-\frac{1}{2}}F\left(\frac{-n}{2}, \frac{1-n}{2}; \frac{1}{2}; u\right).$$

Now, writing again $u = 1+8x$ in the last equation, we have

$$J_n(x) = AF\left(\frac{1-n}{2}, \frac{2-n}{2}; \frac{3}{2}; 1+8x\right) + B(1+8x)^{-\frac{1}{2}}F\left(\frac{-n}{2}, \frac{1-n}{2}; \frac{1}{2}; 1+8x\right).$$

The initial part of this solution can be written in the way

$$J_n(x) = A\sum_{k=0}^{\infty} \frac{\left(\frac{1-n}{2}\right)_k \left(\frac{2-n}{2}\right)_k}{\left(\frac{3}{2}\right)_k\ k!}(1+8x)^k.$$

If we take all values for $k > \frac{n-1}{2}$, we have $\left(\frac{1-n}{2}\right)_k = 0$. So, the series terminates, and the hypergeometric function becomes a hypergeometric polynomial. By choosing

$$A = \frac{(2)_{n-1}}{(n-1)!\ 2^{n-1}},$$

we reach the desired result which completes the proof.

Olver has used the hypergeometric function to express a very wide class of functions, such as Bessel, Legendre, Chebyshev, Hermite, Laguerre, Jacobi, Whittaker, parabolic cylinder, and spherical functions [14]. Olver has also examined their asymptotic behavior and the relations these functions between many special functions. Olver represented the hypergeometric function in the way

$$\mathbf{F}(a,b;c;x) = \frac{1}{\Gamma(c)} F(a,b;c;x) = \sum_{l=0}^{\infty} \frac{(a)_l\,(b)_l}{\Gamma(c+l)} \frac{x^l}{l!}, \qquad (12)$$

and $\mathbf{F}(a,b;c;x)$ called Olver's hypergeometric functions. Additionally, Olver found the following relation between the associated Legendre functions and Olver's hypergeometric functions [15]:

$$\mathbf{F}\left(a, a+\frac{1}{2}; c; z\right) = 2^{c-1}\, z^{(1-c)/2}\, (1-z)^{-a+((c-1)/2)}\, P_{2a-c}^{1-c}\left(\frac{1}{\sqrt{1-z}}\right), \qquad (13)$$

where $|phz| < \pi$ and $|ph(1-z)| < \pi$. The solutions of the associated Legendre equation are called the associated Legendre functions $P_\nu^\mu(x)$ which have the following definitions:

$$P_\nu^\mu(x) = \left(\frac{1+x}{1-x}\right)^{\frac{\mu}{2}} \mathbf{F}\left(\nu+1, -\nu; 1-\mu; \frac{1}{2}-\frac{1}{2}x\right). \qquad (14)$$

Furthermore, the Jacobi polynomials $P_n^{(\alpha,\beta)}(x)$ are the solutions of the Jacobi equation and are defined as follows:

$$P_n^{(\alpha,\beta)}(x) = \frac{(1+\alpha)_n}{n!}\, F\left(-n, 1+\alpha+\beta+n; 1+\alpha; \frac{1-x}{2}\right). \qquad (15)$$

Now, using (11) and (12), the Jacobsthal polynomials $J_n(x)$ can be expressed as follows:

$$J_n(x) = \frac{\sqrt{\pi}\,(2)_{n-1}}{2^n\,(n-1)!}\, \mathbf{F}\left(\frac{1-n}{2}, \frac{2-n}{2}; \frac{3}{2}; 1+8x\right). \qquad (16)$$

The relations between the Jacobsthal polynomials and the associated Legendre functions and the Jacobi polynomials are provided by the following theorem:

Theorem 2.3. The following relations are satisfied by the Jacobsthal polynomials $J_n(x)$:

$$i)\ J_{n+1}(x) = \frac{\sqrt{\pi}\ \ (2)_n\ \ (-2)^{\frac{2n+1}{4}}\ \ \left(\sqrt{x}\right)^{n+1}}{n!\,(x+8x^2)^{\frac{1}{4}}}\, P_{-n-\frac{3}{2}}^{-\frac{1}{2}}\left(\frac{1}{2i\sqrt{2x}}\right),$$

$$ii)\ J_{2n+1}(x) = \frac{n!}{\left(\frac{1}{2}\right)_n\, 2^{2n}}\, P_n^{\left(\frac{1}{2},-2n-1\right)}(-1-16x).$$

Proof: i) Using (13) and (16), we reach at the desired result.

ii) Using (11) and (15), we reach at the desired result.

3. JACOBSTHAL-LUCAS DIFFERENTIAL EQUATIONS

The hypergeometric form for the Jacobsthal-Lucas polynomials and a differential equation named as the Jacobsthal-Lucas differential equation are derived in this section. The Jacobsthal-Lucas polynomials and other known functions or polynomials are then related in specific ways.

Theorem 3.1. The following differential equation is satisfied by the Jacobsthal-Lucas polynomials $j_n(x)$:

$$x(1+8x)y'' - [n-1-(12-8n)x]y' + 2n(n-1)y = 0. \qquad (17)$$

Proof: The desired solution is obtained by using the recurrence relations (5) and (6) along with certain computations.

Theorem 3.2. The following equality is the expression of Jacobsthal-Lucas polynomials $j_n(x)$ in terms of hypergeometric functions:

$$j_n(x) = \frac{1}{2^{n-1}} F\left(\frac{-n}{2}, \frac{1-n}{2}; \frac{1}{2}; 1+8x\right). \qquad (18)$$

Proof: Since Jacobsthal-Lucas polynomials $j_n(x)$ are the solution of (17), we can write

$$x(1+8x)\, j_n'' - [n-1-(12-8n)x]\, j_n' + 2n(n-1)\, j_n = 0.$$

In this case, applying the mapping $u = 1+8x$, we have

$$u(1-u)\frac{d^2 j_n}{du^2} + \left(\frac{1}{2} - \left(\frac{3}{2} - n\right)u\right)\frac{dj_n}{du} - \frac{n(\mathrm{n}-1)}{4}\, j_n = 0.$$

The following constants are obtained by comparing the last equation with (7):

$$c = \frac{1}{2}, a = \frac{-n}{2}, b = \frac{1-n}{2}.$$

The general solution of (17) is

$$j_n(u) = AF\left(\frac{-n}{2}, \frac{1-n}{2}; \frac{1}{2}; u\right) + Bu^{\frac{1}{2}} F\left(\frac{1-n}{2}, 1-\frac{n}{2}; \frac{3}{2}; u\right).$$

Now, writing again $u = 1+8x$ in the last equation, we have

$$j_n(x) = AF\left(\frac{-n}{2}, \frac{1-n}{2}; \frac{1}{2}; 1+8x\right) + B(1+8x)^{\frac{1}{2}} F\left(\frac{1-n}{2}, 1-\frac{n}{2}; \frac{3}{2}; 1+8x\right).$$

The initial part of this solution can be written in the way

$$j_n(x) = A \sum_{k=0}^{\infty} \frac{\left(\frac{-n}{2}\right)_k \left(\frac{1-n}{2}\right)_k}{\left(\frac{1}{2}\right)_k\ k!} (1+8x)^k.$$

If we take all values for $k > \frac{n}{2}$, we have $\left(\frac{-n}{2}\right)_k = 0$. So, the series terminates, and the hypergeometric function becomes a hypergeometric polynomial. Then, by choosing

$$A = \frac{1}{2^{n-1}},$$

we reach the desired result which completes the proof.

Using (12) and (18), the Jacobsthal-Lucas polynomials $j_n(x)$ can be expressed as follows:

$$j_n(x) = \frac{\sqrt{\pi}}{2^{n-1}} \mathbf{F}\left(\frac{-n}{2}, \frac{1-n}{2}; \frac{1}{2}; 1+8x\right). \qquad (19)$$

The relations between the Jacobsthal-Lucas polynomials and the associated Legendre functions and the Jacobi polynomials are provided by the following theorem:

Theorem 2.3. The following relations are satisfied by the Jacobsthal-Lucas polynomials $j_n(x)$:

$$i)\ j_{2n}(x) = \sqrt{\pi}\ (-2)^{n-\frac{1}{4}} \left(\frac{1}{x}+8\right)^{\frac{1}{4}} (2x)^n\ P^{\frac{1}{2}}_{-2n-\frac{1}{2}}\left(\frac{1}{2i\sqrt{2x}}\right),$$

$$ii)\ j_{2n}(x) = \frac{n!}{\left(\frac{1}{2}\right)_n\ 2^{2n-1}}\ P_n^{\left(-\frac{1}{2},-2n\right)}(-1-16x).$$

Proof: i) Using (13) and (19), we reach at the desired result.

ii) Using (15) and (18), we reach at the desired result.

4. CONCLUSION

This article provides the theorems including a differential equation and a hypergeometric form of Jacobsthal polynomials. In a similar manner, we obtain these theorems for the Jacobsthal-Lucas polynomials. These equations and hypergeometric forms can be utilized

- Physical Applications: It can be identified which physical systems (such as quantum mechanics, optics, or statistical physics) the equation applies to, and which physical quantities it can model.

- Asymptotic Solutions:

It is possible to describe potential asymptotic methods for both large and small parameter values.

- Numerical Methods:

It can be specified how the equation can be solved numerically and which computational methods are appropriate.

Lastly, we found some relations between the Jacobsthal and Jacobsthal-Lucas polynomials and known special functions and orthogonal polynomials by employing the formula in terms of Olver's hypergeometric functions.

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INFRARED-BASED DEFECT DETECTION IN SOLAR PANELS USING CNNS

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ABSTRACT

Solar photovoltaic (PV) systems are becoming an important source of clean energy worldwide, but their performance depends on the physical condition of the solar panels. Over time, panels can show different types of faults, such as cracks, hotspots, dust gathering, diode failures, short circuits, and other damage. How we used to detect faults, for example, cracks: we used EL imaging, visual inspection, and the I-V curve, for hotspots, we used temperature sensors and the I-V curve, for dust, we also used similar method, visual inspection. These problems reduce the power output and can lead to safety risks, like overheating and fire hazards. Because large solar farms have thousands of panels, checking them manually is difficult, slow, and not accurate. That's the reason we focus on automatic fault detection using image processing and deep learning. The reason we focus on automatic fault detection is because small cracks cannot be localized exactly, and the hotspots cannot map the whole panel. The latest advances in deep learning, especially Convolutional Neural Networks (CNN), have improved the accuracy and reliability of PV fault detection and classify the different types of faults with precision. In this paper, we will show that using CNN, the accuracy reached up to 99.91% (VGG16). And Infrared Thermography (IRT) for automatic fault detection in PV modules. IRT finds temperature differences, and CNN analyzes those differences to automatically identify PV faults with very high accuracy. Let's take for example cracks; they cause a thin hot line that the IRT shows as a warm streak, and then the CNN identifies the edge pattern. After that the maintenance receives the fault type, location, and severity, so they act fast. Some studies used advanced CNN architectures like VGG16: which is type of CNN with 16 layers. It's good at image classification; Mask R-CNN: analyzes thermal images effectively and highlights the exact area on the panel where the defect is with accuracy, and EfficientNet detects faults like hotspots, cracks, and dust with high precision. In this paper we will show that IRT and CNN are breakthrough technology for safe, efficient, and intelligent solar panel monitoring.

Keywords: Photovoltaic (PV) systems, infrared thermography (IRT), CNN, deep learning, defect detection, fault classification, VGG16, Mask R-CNN, EfficientNet.

INTRODUCTION

Solar photovoltaic (PV) systems are expanding rapidly worldwide yet they remain highly sensitive to defects that gradually reduce their performance. Even small issues such as dust hotspots micro cracks diode failures and shading can lead to annual efficiency losses ranging between 0.5% and 1%. These losses may sound minor but over the lifetime of a solar plant they translate into major reductions in power output and significant financial impact [1]. More importantly certain defects if not detected early can create safety risks such as overheating and fire hazards. As global solar capacity continues to rise and large-scale solar farms become more common maintaining the health and safety of PV modules has become a critical challenge for researcher's engineers and system operators. Traditionally PV module inspection relied on manual checks and electrical measurements. While these methods can detect overall performance decline, they struggle to pinpoint the exact location or type of defect [2]. Many faults especially micro cracks and early-stage hotspots are not visible to the naked eye and do not immediately affect the electrical output in a measurable way. Manual inspection is slow labor intensive and often impractical for solar farms that contain thousands of panels. Electrical measurements such as (I, V) curve analysis can indicate abnormal behavior but they cannot reveal where the problem is or provide detailed insight into its physical characteristics. These limitations highlight the need for more advanced diagnostic tools that can detect faults accurately quickly and with minimal human intervention. Infrared thermography has emerged as one of the most promising technologies for this purpose. Since many PV defects cause localized heating thermal imaging can clearly reveal anomalies in the form of temperature differences [1],[3]. Thermal cameras can scan large areas rapidly and they can be mounted on drones allowing for inspection of large solar installations without shutting down the system. Unlike methods that require dark environments or physical contact with the panels infrared imaging works under normal operating conditions and provides immediate visual interpretation of hotspots shading effects diode issues and other thermal abnormalities. Its non-destructive nature and speed make it a valuable tool for modern PV maintenance. Alongside advances in imaging artificial intelligence specifically deep learning has transformed how thermal images are analyzed. Convolutional Neural Networks (CNNs) have proven extremely effective in automatically extracting complex features from images without requiring manual feature design. When applied to infrared images of PV modules, CNNs can distinguish between normal and faulty panels identify specific defect types and even classify multiple fault categories [3]. Deep learning excels at detecting subtle patterns such as small temperature gradients or irregular shapes that human inspectors may overlook. Over the past few years, a wide variety of CNN architectures have been explored for PV fault detection. Some models are designed to be lightweight and fast suitable for real time applications and embedded devices. Others focus on extracting deeper features using more sophisticated layers improving accuracy even in noisy or low-resolution images [4]. Enhancements such as attention mechanisms multi scale feature extraction and edge guided learning have been proposed to handle challenges like blurred boundaries and overlapping thermal signatures. Data augmentation and balanced datasets have further improved the performance of these models by making them more robust to variations in lighting weather and imaging conditions [5]. As a result, deep learning systems now achieve very high accuracy across both binary classification (normal vs. faulty) and multi class classification (different defect categories).

However, despite these advancements important gaps remain. Many existing deep learning models are trained on controlled datasets that do not fully represent the variability found in real-world conditions. Outdoor thermal images often contain noise reflections uneven heating and environmental effects that degrade model performance. Models trained in one climate or

region may not generalize well to another. Another major gap is that most systems classify only one fault per image even though real PV modules often experience multiple simultaneous issues for example dust buildup combined with partial shading or cracks that later develop into hotspots.

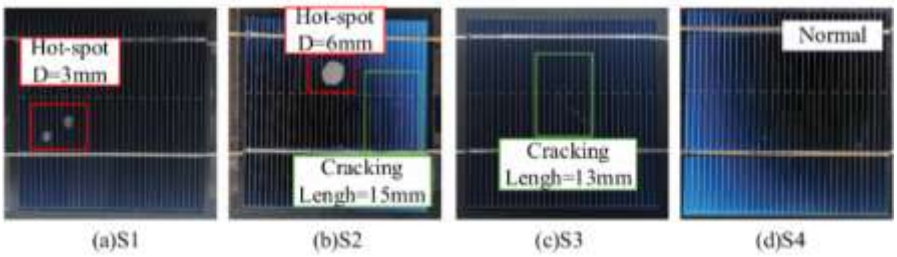

Figure 1.PV cells with different defects types

Current models still struggle with multilabel classification limiting their usefulness in complex field conditions [6]. Additionally, some highly accurate CNN architectures require powerful hardware making them difficult to deploy on drones or portable inspection devices used in everyday operations. These challenges highlight the need for a more comprehensive and robust approach to PV fault diagnosis. An ideal system would combine the strengths of infrared thermography with advanced deep learning techniques while addressing real world variability noise and multilabel scenarios. It would also be efficient enough to run on lightweight hardware for real time inspection. The objective of this research is to develop an improved CNN based system capable of accurately detecting and classifying PV module defects using infrared thermographic images. The study aims to create a model that performs reliably across diverse conditions identifies multiple fault types and maintains high accuracy without requiring heavy computational resources. The work includes exploring enhanced feature extraction techniques integrating attention or edge focused modules and optimizing the model for practical field deployment.

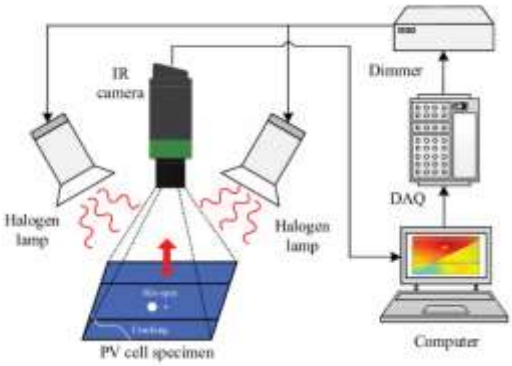

Figure 2.Photo thermal radiation infrared thermography detection schematic diagram

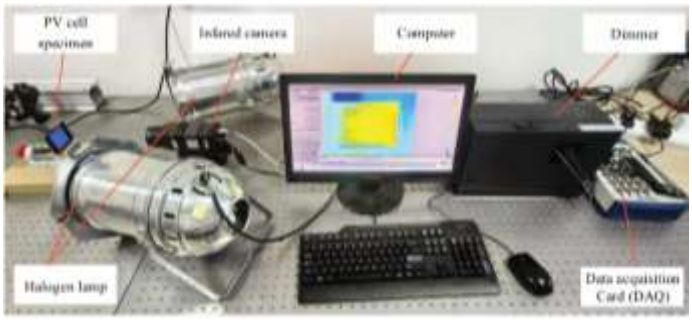

Figure 3.Photo thermal radiation infrared thermography detection system

The main research question guiding this work is:

Can an optimized CNN model supported by advanced image processing and robust feature extraction provide more accurate reliable and real time fault detection for photovoltaic modules compared to existing inspection techniques?

The hypothesis is that a carefully designed CNN architecture combined with suitable preprocessing augmentation and learning strategies will greatly improve detection accuracy reduce false classifications and provide a more practical solution for real world PV monitoring.

METHODS

Research Design

This study uses an experimental computational research design to investigate whether a refined convolutional neural network (CNN) can accurately detect faults in photovoltaic (PV) modules using infrared thermographic images. The design suits the research question because PV faults naturally create temperature variations and infrared cameras capture these patterns directly [1]. Deep learning is ideal for interpreting these thermal signatures as CNNs are built to extract edges textures and spatial structures [3]. By training and testing models under controlled conditions the design allows systematic comparison of performance evaluation of generalization ability and identification of sources of classification error. This approach combines physical principles with modern computational learning techniques making it appropriate for developing an intelligent PV diagnostic tool.

Population and Sample

The population consists of thermal images representing PV modules in real operating conditions. The sample includes infrared images that clearly display PV panel surfaces and contain identifiable thermal patterns [2]. Only images with sufficient resolution and visible temperature gradients are included. Images that are unreadable excessively distorted or lacking meaningful thermal information are excluded ensuring the model learns from reliable data. The final sample contains both normal and faulty modules so the CNN can distinguish healthy temperature distributions from anomalies. Keeping the sample limited to infrared imagery ensures consistency with the thermal behavior of PV faults and avoids mixing data that carry different physical meanings.

Tools and Procedures

Infrared thermal images serve as the primary data source revealing hotspots shading effects cracks and other anomalies created by changes in temperature flow within the PV structure [1]. The study uses Python based deep learning frameworks to build and optimize CNN architectures. Images are preprocessed through resizing and normalization to create uniform input conditions while augmentation introduces slight variations that improve generalization

[4]. The CNN processes each image through multiple convolutional layers that extract thermal features of increasing complexity. Training involves minimizing classification error and evaluating performance on unseen data to ensure robustness [5]. Instead of listing step by step procedures the methodology is presented as a conceptual workflow that reflects academic expectations for a methods section without procedural formatting.

Analysis Plan

The analysis focuses on measuring the model's ability to classify PV conditions accurately. The dataset is divided into training validation and testing subsets to provide an unbiased performance estimate. Evaluation includes accuracy precision recall and F1 score which together provide a balanced view of how well the model identifies different faults [6]. Confusion matrices help visualize misclassifications and highlight which types of defects are most difficult to detect. Training behavior is monitored through loss and accuracy curves to ensure the model is not overfitting. A GPU enabled environment supports efficient training and parameter optimization. This analysis plan provides the structure needed to assess how effectively the CNN interprets thermal images and handles real-world variability.

Mathematical Derivations

The CNN's core operation is convolution. Given a thermal image I (x, y) and a kernel

K (i, j) the extracted feature map is

$$F(x,y) = \sum_i \sum_j I\, I(x-i, y-j)K(i,j)$$

This calculation identifies temperature edges and gradients linked to PV faults [3].

The network outputs class probabilities using the SoftMax function:

$$\widehat{y_c} = \frac{e^{z_c}}{\sum_{k=1}^{C} e^{z_k}}$$

Model training minimizes cross entropy loss defined as:

$$\mathrm{L} = -\sum_{c=1}^{C} y_c \log(\widehat{y_c})$$

Parameters are updated using gradient descent:

$$\theta_{t+1} = \theta_t - n\frac{\partial L}{\partial \theta}$$

Performance is assessed using standard formulas:

$$Precision = \frac{TP}{TP+FP} \quad Recall = \frac{TP}{TP+FN}$$
$$F1 = 2 \times \frac{precision \times recall}{precision + recall}$$

where TP: number of true positives, TN: number of true negatives, FP: number of false positives, FN: number of false negatives.

These mathematical expressions summarize how features are extracted, how the model learns, and how evaluation metrics are computed [4].

RESULTS AND CONCLUSION

The developed convolutional neural network showed strong ability to recognize and classify thermal anomalies in photovoltaic (PV) modules using infrared images. The model demonstrated clear improvement during training with decreasing loss and rising accuracy indicating that it successfully learned meaningful thermal patterns rather than memorizing the data [3],[7]. When evaluated on unseen images the network maintained high accuracy confirming its capacity to generalize across different conditions [4],[8]. Precision and recall values were strong meaning the model correctly identified faults when present and avoided unnecessary false alarms on healthy modules. Thermal defects such as hotspots shading induced heating and local temperature rises were detected with particularly high sensitivity reflecting the CNN's strength in identifying clear thermal gradients [1],[5].

Some challenges emerged in differentiating defects with very similar thermal characteristics such as mild shading and certain soiling conditions. These patterns occasionally overlapped leading to a small number of misclassifications. However, the overall misclassification rate remained low and the model still performed reliably across all categories. The confusion matrix confirmed that most predictions clustered correctly within their true class showing that the network developed a stable understanding of the differences between normal and faulty modules. Data augmentation also contributed significantly to the model's performance by exposing the CNN to variations in brightness angle and scale making it more robust to real world conditions [4],[9].

In terms of computational behavior, the model achieved fast processing times demonstrating potential suitability for live inspection scenarios using drones or portable thermal devices. Despite its efficiency there was no meaningful drop in classification accuracy suggesting the architecture is well balanced between complexity and practicality [6],[10].

In conclusion the results of this study show that deep learning combined with infrared thermography provides an effective and reliable approach for automated PV fault detection. The model proved capable of accurately interpreting thermal behavior and identifying a range of fault types under diverse imaging conditions. This confirms the initial hypothesis that a refined CNN architecture can outperform traditional inspection methods which often struggle with subtle or early-stage defects [2],[3]. The approach also offers benefits in terms of speed consistency and scalability, making it a promising tool for modern solar farm operations [5],[10].

Although highly effective the study highlights areas for future improvement. Expanding the dataset with more examples of visually similar defects would help reduce confusion in borderline cases. Additionally integrating fault localization or multilabel classification could enable the system not only to identify the type of fault but also to highlight its exact position and detect multiple issues simultaneously. Nevertheless, the findings establish a strong foundation for intelligent PV monitoring systems and demonstrate the significant potential of deep learning in supporting the reliability and sustainability of solar energy production [8],[9].

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DETERMINATION OF POTATO LATE BLIGHT DISEASE MANAGEMENT STRATEGIES IN ÇUKUROVA REGION CONDITIONS

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ABSTRACT

Potato late blight, caused by *Phytophthora infestans* (Mont.) de Bary, is one of the most economically destructive diseases of potato production worldwide. The disease is estimated to account for global losses of 3–10 billion USD annually in terms of crop damage and fungicide costs, and growers in many production regions apply 10–20 fungicide sprays per season, increasing to 20–30 applications in tropical areas. In Türkiye, the earliest potato harvest takes place under the conditions of the Çukurova region, which makes early-season potato production a strategically important sector for both the domestic market and export. Growers in this region typically apply protective fungicides against late blight every 7–10 days, resulting in 10–12 applications per season. In the absence of effective control, yield losses may reach up to 100%. This study, based on trials conducted between 2013 and 2016 in the Çukurova region, aims to optimize fungicide timing and frequency against potato late blight using climate-based forecasting and early warning system approaches. Compared with calendar-based fixed-interval sprays, a fungicide program driven by meteorological data reduced the number of applications by approximately 25–30% without adversely affecting disease severity or yield. Within the integrated approach, disease incidence was lowest and economic return was highest. A simulation model based on five-day reinfection periods successfully reflected the observed disease progress across different micro-regions of Çukurova, and predicted yield losses deviated from observed values by less than 5%, confirming its potential for local deployment. Overall, the findings demonstrate that the fixed-schedule fungicide programs still widely used under Çukurova conditions result in substantial economic and environmental costs. When combined with cultural practices and the use of resistant cultivars, climate-based early warning systems can enable more sustainable crop protection against potato late blight, achieving effective disease suppression with fewer fungicide applications.

Keywords: *Solanum tuberosum Phytophthora infestans*, late blight, decision support systems, Çukurova region, fungicide

ÖZET

Patates mildiyö hastalığı (geç yanıklık), etmeni *Phytophthora infestans* (Mont.) de Bary dünya genelinde patates üretiminde en büyük ekonomik kayıplara yol açan hastalıklardan biridir. Hastalık, küresel ölçekte her yıl 3–10 milyar ABD doları düzeyinde ürün ve ilaçlama kaybına neden olmakta, birçok üretim bölgesinde çiftçiler sezon boyunca 10–20, tropik bölgelerde ise 20–30'a varan sayıda fungisit uygulaması yapmak zorunda kalmaktadır. Türkiye'de en erken patates hasadı Çukurova koşullarında gerçekleşmekte; bu da erken sezon patates yetiştiriciliğini hem iç pazar hem de ihracat açısından stratejik bir üretim kolu hâline getirmektedir. Bölgedeki üreticiler, pates mildiyö hastalığına karşı her 7–10 günde bir koruyucu fungisit uygulamakta ve bu durum sezon başına 10–12 uygulamaya ulaşmaktadır. Uygun bir mücadele yapılmadığında verim kayıpları %100'e kadar çıkabilmektedir. Bu çalışma, 2013–2016 yılları arasında Çukurova Bölgesi'nde yürütülen patates mildiyö hastalığına karşı fungisit uygulama zamanlamasının ve sıklığının iklim verilerine dayalı tahmin erlken uyarı sistemleri yaklaşımlarıyla optimize edilmesini amaçlamaktadır. Meteorolojik verilere dayalı fungisit programı, sabit aralıklı uygulamalara kıyasla hastalık şiddetini veya verimi olumsuz etkilemeden ilaçlama sayısını yaklaşık %25–30 oranında azaltmıştır. Entegre yaklaşımda hem hastalık insidansı en düşük, hem de ekonomik getiri en yüksek düzeyde bulunmuştur. Beş günlük yeniden enfeksiyon dönemlerine dayalı simülasyon modeli, Çukurova'nın farklı mikro bölgelerinde gözlenen hastalık gelişimini yüksek doğrulukla yansıtmış ve tahmin edilen verim kayıpları, gözlenen değerlerle %5'in altında sapma göstermiştir. Elde edilen sonuçlar, Çukurova koşullarında hâlen yaygın olan sabit programlı fungisit uygulamalarının hem ekonomik hem de çevresel açıdan ciddi kayıplara neden olduğunu ortaya koymaktadır. İklim verilerine dayalı erken uyarı sistemleri, kültürel uygulamalar ve dayanıklı çeşitlerin kullanımıyla desteklendiğinde, Patates mildiyö hastalığı ile mücadelede daha az sayıda ilaçlama ile daha sürdürülebilir bir ürün koruma stratejisi oluşturulabileceğini göstermektedir.

Anahtar Kelimeler: *Solanum tuberosum*, *Phytophthora infestans*, geç yanıklık, erken uyarı sistemi, Çukurova, fungisit

1. Giriş

Patates (*Solanum tuberosum* L.), dünyada insan beslenmesinde buğday, mısır ve pirinçten sonra dördüncü sırada yer alan temel gıda bitkilerinden biridir. Gerek taze tüketimde gerekse sanayi ve tohumluk sektörlerinde stratejik öneme sahiptir. Ancak patates üretimi, fungal bakteriyel ve viral hastalıklar başta olmak üzere pek çok biyotik stres faktörüyle kısıtlanmaktadır. Bunlar arasında, patates geç yanıklığı, etmeni *Phytophthora infestans* (Mont.) de Bary hem yeşil aksam hem de yumrularda ağır tahribata yol açan en yıkıcı hastalıktır. *P. infestans* uygun çevre koşullarında çok kısa sürede tüm tarlayı infekte edebilmekte; yaprak yüzeyinin büyük bir kısmını nekrotik hâle getirerek fotosentez kapasitesini düşürmekte, aynı zamanda yumrularda da çürüklük oluşturarak depolama kayıplarına neden olmaktadır. Hastalık, tarihsel olarak İrlanda Patates Kıtlığı ile özdeşleşmiş olsa da, günümüzde de dünya genelinde her yıl milyarlarca dolarlık ürün kaybı ve yoğun fungisit kullanımına yol açmaya devam etmektedir (Fry ve ark., 2015). Etmenin genetik esnekliği, kısa sürede yeni ırklar oluşturabilmesi ve fungisitlere direnç geliştirebilmesi, hastalığın yönetimini daha da güçleştirmektedir (Majeed, 2017; Blossei ve ark., 2022).

Çukurova Bölgesi (Adana ve çevresi), Türkiye'de hem sofralık hem de tohumluk patates üretimi açısından öne çıkan önemli üretim merkezlerinden biridir. Bölgenin ılıman kış koşulları, erken ekim ve erkenci hasat imkânı sağlamaktadır. Aralık sonu–Ocak sonu döneminde yapılan ekimler, Nisan sonu–Haziran başı arasında turfanda hasatla sonuçlanmakta ve bölge hem iç pazara hem de ihracata erken patates arz eden stratejik bir konumda bulunmaktadır. Ancak aynı iklim özellikleri, özellikle ilkbahar aylarında yüksek oransal nem, uzun yaprak ıslaklığı ve 15–22 °C aralığındaki sıcaklıklar nedeniyle geç yanıklık epidemileri için son derece elverişli koşullar yaratmaktadır (Günaçtı et al., 2019). Bu nedenle bölgede üreticiler, hastalık ortaya çıkmadan "takvim esaslı" koruyucu fungisit uygulamalarına yönelmektedir. Bölgesel gözlemler, pek çok işletmede sezon boyunca 10–12'ye varan sayıda ilaçlama yapıldığını ve geç yanıklık fungisitlerinin patates üretiminde kullanılan toplam fungisit miktarının önemli bir bölümünü oluşturduğunu göstermektedir. Bu durum, hem üretim maliyetlerini artırmakta, hem de çevresel yük ve direnç gelişimi açısından risk taşımaktadır.

Son otuz yılda, geç yanıklığa karşı fungisit kullanımını rasyonelleştirmek amacıyla çok sayıda hava durumu temelli tahmin modeli ve erken uyarı sistemi geliştirilmiştir. Ullrich ve Schrödter'in negatif prognosisi, Winstel modeli, Blitecast, PhytoPRE, Mileos ve NEGFRY gibi sistemler; sıcaklık, bağıl nem, yaprak ıslaklığı ve yağış verilerini kullanarak enfeksiyon riskini sayısallaştırmakta ve ilaçlama kararlarına bilimsel bir temel sunmaktadır (Schepers, 2004; Small ve ark., 2015; Meno ve ark., 2024; Castaño-Serna ve ark., 2025). Buna paralel olarak, Rusya, Almanya ve Hollanda'da yürütülen çalışmalar, yeniden enfeksiyon için elverişli beş günlük dönemlerin sayısına bağlı olarak verim kaybını tahmin eden simülasyon modellerinin, uzun dönemli meteorolojik verilerle kalibre edildiğinde güvenilir çıktılar üretebildiğini ortaya koymuştur (Filippov ve ark., 2018). Türkiye'de Çukurova koşullarında geç yanıklık tahmin modellerinin ilk sistematik değerlendirmelerinden biri, 2013–2014 yıllarında Adana'da yürütülen ve Winstel, Blitecast ve Ullrich–Schrödter modellerinin karşılaştırıldığı çalışmalarla gerçekleştirilmiş; bu çalışmalarda Winstel modelinin yerel koşullarda enfeksiyon tahmininde daha başarılı olduğu bildirilmiştir (Günaçtı ve Ay, 2021).

Bu çalışmada, Çukurova koşullarında ticari üretim koşullarında yürütülen çok yıllık denemeler kullanılarak, (i) hava durumu ile geç yanıklık epidemileri ve verim kaybı arasındaki ilişkilerin ortaya konulması, (ii) sabit aralıklı fungisit programları ile meteoroloji tabanlı ilaçlama stratejilerinin ve kültürel önlemlerle desteklenen entegre bir yaklaşımın karşılaştırılması ve (iii)

beş günlük yeniden enfeksiyon dönemlerine dayalı bir simülasyon modelinin bölge koşullarına uyarlanarak doğruluğunun değerlendirilmesi amaçlanmıştır.

2. Materyal ve Yöntem

2.1 Çalışma alanı ve yetiştirme sistemi

Arazi çalışmaları, 2013–2016 yılları arasında Çukurova Bölgesi'nde (Adana ili ve çevresi) ticari patates tarlalarında yürütülmüştür. Bölge, Akdeniz ikliminin tipik özelliklerini taşımakta olup, kışları ılık ve yağışlı, ilkbaharı nispeten ılık ve nemlidir. Erken sezon patates ekimleri genellikle Aralık sonu–Ocak sonu döneminde yapılmakta, hasat ise Nisan sonu–Haziran başında gerçekleştirilmektedir. Denemeler, bölgedeki ana üretim alanlarını temsil edecek şekilde, yağmurlama veya karık sulama yapılan tarlalarda kurulmuştur (Günaçtı ve Ay, 2021). Çalışmalarda, bölge üreticilerinin yaygın olarak kullandığı sofralık patates çeşitleri kullanılmıştır. Ekim sıklığı, gübreleme ve sulama rejimleri, üreticinin mevcut uygulamalarını yansıtacak şekilde düzenlenmiş; böylece sonuçların ticari koşullara uyumlu olması hedeflenmiştir.

2.2 Meteorolojik Veriler

Her bir deneme alanına, otomatik meteoroloji istasyonu iMETOS® kurulmuş ve vejetasyon süresince saatlik hava sıcaklığı (°C), bağıl nem (%), yaprak ıslaklığı (saat) ve yağış (mm) verileri kaydedilmiştir. Kayıtlar düzenli olarak kontrol edilmiş, arıza veya kesinti durumlarında yakın resmi meteoroloji istasyonlarından alınan verilerle makul ölçüde tamamlanmıştır (Günaçtı ve Ay, 2021). Bu veriler kullanılarak; bağıl nemin %90'ın üzerinde seyrettiği saatler, 8–10 saatten uzun yaprak ıslaklığı periyotları ve 10–25 °C aralığındaki sıcaklıklarla çakışan yağış/sulama olayları gibi enfeksiyon açısından kritik meteorolojik göstergeler hesaplanmış, ayrıca ardışık beş günlük verilere göre özetlenmiştir (Schepers, 2004; Castaño-Serna ve ark., 2025).

2.3 Hastalık gözlemleri

Patates mildiyö hastalığı, çıkıştan itibaren vejetasyon sonuna kadar haftalık aralıklarla değerlendirilmiştir. Her parselde sabit bitkiler seçilmiş; yaprak yüzeyinde hastalıkla kaplı alan, görsel tahmin ölçekleri kullanılarak yüzde (%) olarak belirlenmiştir. Elde edilen değerlerden, her parsel ve yıl için hastalık ilerleyişinin nicel göstergesi olarak, hastalık ilerleme eğrisi altında kalan alan (AUDPC) hesaplanmıştır (Majeed, 2017). Hastalık belirtilerinin ilk görüldüğü dönemlerde, tipik lezyonlara sahip yaprak örnekleri laboratuvara getirilmiş; etmen *P. infestans*, sporangi ve sporangi taşıyıcılarının mikroskobik incelenmesi ve gerekli durumlarda selektif besi yerlerinde izolasyon yoluyla doğrulanmıştır (Günaçtı ve Ay, 2021). Hasat döneminde, her parselde toplam ve pazarlanabilir yumru verimi (t ha^{-1}) belirlenmiştir. Pazarlanabilir verim, geç yanıklık lekesi içermeyen ve pazarlama standartlarına uygun irilik ve dış kalite kriterlerini taşıyan yumruları kapsamıştır.

2.4. Fungisit uygulamaları

Çalışmada dört farklı mücadele stratejisi karşılaştırılmıştır:

Sabit aralıklı fungisit programı (Çiftçi uygulaması)

Bu uygulamada fungisitler, hava koşulları dikkate alınmaksızın, sıranın kapanmasından itibaren 7–10 günde bir olacak şekilde sezon boyunca düzenli olarak uygulanmıştır. Sezon sonunda uygulama sayısı 10–12'ye ulaşmıştır. Kullanılan preparatlar, bölgede yaygın olarak tavsiye edilen koruyucu ve sistemik fungisit karışımlarından oluşmuştur.

İklim verilerine dayalı fungisit programı (Tahmin uyarı modeli)

Bu stratejide ilaçlama kararları, Blitecast ve PhytoPRE karar kurallarından uyarlanan yerel bir karar destek algoritması kullanılarak verilmiştir (Schepers, 2004; Small ve ark., 2015; Castaño-Serna ve ark., 2025). Otomatik istasyonlardan alınan saatlik sıcaklık, bağıl nem ve yaprak ıslaklığı verileri ile risk birimleri hesaplanmış; birikimli riskin belirli eşikleri aştığı veya enfeksiyon olasılığının kritik düzeylere ulaştığı dönemlerde fungisit uygulaması önerilmiştir.

Entegre Mücadele programı

Entegre yönetim yaklaşımı; yukarıda belirtilen iklim tahminine dayalı fungisit programına ek olarak sertifikalı, hastalıksız tohumluk yumru kullanımı,en az 3–4 yıllık münavebe ile patates, hasat sonrası artıkların imhası gibi kültürel mücadele yöntemlerini de içermektedir. Böylece tarladaki primer inokulum kaynağının azaltılması ve tahmin uyarı sistemlerinin daha düşük başlangıç risk düzeyinde çalışması hedeflenmiştir (Majeed, 2017).

Simülasyon modeli destekli strateji

Dördüncü yaklaşımda, Rusya, Almanya ve Hollanda'da geliştirilmiş ve uzun yıllara ait veri setleriyle doğrulanmış, yeniden enfeksiyon için elverişli beş günlük dönem sayısına dayalı bir simülasyon modeli (Filippov ve ark., 2018) Çukurova koşullarına uyarlanmıştır. Model, her sezon ve mikro bölge için gerçek meteorolojik verileri kullanarak; farklı ilaçlama sıklıklarının (6, 8, 10 uygulama) beklenen verim kaybı üzerindeki etkisini tahmin etmiş; bu çıktılar sabit programlı ve tahmin uyarı modeli yönlendirmeli uygulamaların sahadaki performansıyla karşılaştırılmıştır.

2.5 Veri analizi

Her yıl ve her mücadele stratejisi için AUDPC ve verim değerleri varyans analizine (ANOVA) tabi tutulmuş; anlamlı bulunan faktörler için ortalamalar, uygun çoklu karşılaştırma testleriyle ($P \leq 0,05$) kıyaslanmıştır. Hastalık şiddeti, meteorolojik değişkenler, beş günlük yeniden enfeksiyon periyotlarının sayısı ve verim kaybı arasındaki ilişkiler korelasyon ve regresyon analizleriyle incelenmiştir.

3. Bulgular

3.1 İklim verileri ve epidemi gelişimi

Üç yıllık gözlemler, Çukurova koşullarında patates mildiyö hastalığı epidemilerinin, yüksek bağıl nem (%90'ın üzerinde), uzun süreli yaprak ıslaklığı ve 15–22 °C aralığındaki sıcaklıklarla yakından ilişkili olduğunu göstermiştir. Özellikle art arda birkaç beş günlük periyotta bu koşulların aynı anda sağlandığı dönemlerin, hastalığın tarlada hızla yayıldığı yüksek risk koşullarını oluşturduğu belirlenmiştir. Mart ve Nisan aylarında uzun yıllar ortalamasının üzerinde yağış alan sezonlarda, hastalığın çıkışı daha erken olmuş ve hastalık ilerleme eğrileri daha dik seyretmiştir. Buna karşın, erken sezonda yağışın görece düşük olduğu ve yaprak ıslaklığı periyotlarının kısa kaldığı yıllarda, patates mildiyö hastalığı epidemileri daha yavaş gelişmiş ve özellikle iyi havalanan, uygun sıra arası mesafeye sahip tarlalarda sınırlı kalmıştır.

3.2 Sabit programlı fungisit uygulamaları

Takvim esaslı fungisit programları, yüksek riskli yıllarda kabul edilebilir düzeyde hastalık kontrolü sağlayabilmiş, ancak bunu yüksek uygulama sayısı göze alınarak gerçekleştirmiştir. Özellikle kurak seyreden sezonlarda, enfeksiyon riskinin model çıktılarında düşük olduğu uzun aralıklar boyunca ilaçlama yapılmaya devam edilmiş; bu da gereksiz fungisit kullanımı ve girdi maliyetine neden olmuştur. Yoğun ilaçlamaya rağmen, hava koşullarının üst üste birkaç gün boyunca son derece elverişli olduğu dönemlerde, tarlalarda yine de belirgin hastalık belirtileri

gözlenmiştir. Benzer bulgular, Avrupa'nın farklı patates üretim bölgelerinde yürütülen çalışmalarda da bildirilmiştir (Schepers, 2004; Small ve ark., 2015; Majeed, 2017; Castaño-Serna ve ark., 2025).

3.3 İklim verilerine dayalı fungisit programı

İklim verilerine dayalı tahmin uyarı sistemi, sabit programlı uygulamalara kıyasla toplam fungisit sayısını önemli ölçüde azaltmıştır. Yıllar genelinde ortalama olarak, ilaçlama sayısında yaklaşık %25–30'luk bir azalma sağlanmış; buna karşın nihai hastalık şiddetinde anlamlı bir artış veya pazarlanabilir verimde istatistiksel olarak önemli bir azalma gözlenmemiştir. Bu stratejide, uygulamalar daha çok modeller tarafından "yüksek riskli" olarak tanımlanan dönemlerde yoğunlaşmış; enfeksiyon riskinin düşük olduğu bölümlerde ise ilaçlamadan kaçınılmıştır. Böylece uygulamalar zamansal olarak yoğunlaştırılmış; kurak veya nispeten düşük riskli yıllarda sabit programa göre daha uzun ilaçsız dönemler mümkün olmuştur. Bulgular, farklı ülkelerde tahmin uyarı sistemi temelli yönetimin, benzer şekilde daha az uygulama ile etkin hastalık kontrolü sağlayabildiğini bildiren çalışmalarla uyumludur (Schepers, 2004; Small ve ark., 2015; Meno ve ark., 2024).

3.4 Entegre yönetim

Entegre yönetim stratejisi, üç yıllık dönem boyunca en düşük hastalık insidansı ve en yüksek pazarlanabilir verim değerlerini sağlamıştır. Sertifikalı tohumluk kullanımı, münavebe ve enfekteli atıkların tarladan uzaklaştırılmasıyla, tarladaki primer inokulum önemli ölçüde düşmüş; bu da epideminin başlamasını geciktirmiş ve maksimum hastalık şiddetini azaltmıştır. Bu koşullar altında çalışan tahmin uyarı sistemi sınırlı sayıda, ancak daha isabetli zamanlanmış ilaçlama önermiştir. Sonuç olarak hem toplam uygulama sayısı hem de birim ürün başına düşen kimyasal girdi miktarı önemli ölçüde düşmüştür. Entegre mücadelenin bu üstünlüğü, patates mildiyö hastalığı için önerilen uluslararası entegre mücadele çerçeveleriyle de uyumlu bulunmuştur (Majeed, 2017).

3.5 Beş günlük yeniden enfeksiyon dönemlerine dayalı simülasyon modeli

Çalışmada uyarlanan, yeniden enfeksiyon için elverişli beş günlük dönem sayısına dayalı simülasyon modeli (Filippov ve ark., 2018), Çukurova koşullarında elde edilen saha verileriyle karşılaştırıldığında, hastalığın zaman içindeki gelişimini ve buna bağlı verim kayıplarını yüksek doğrulukla yansıtmıştır. Model, her sezon ve mikro bölge için düşük, orta ve yüksek risk profiline sahip yılları doğru şekilde ayırt edebilmiş; farklı varsayımsal ilaçlama senaryoları için öngördüğü verim kayıpları, gözlenen değerlerle genel olarak %5'in altında sapma göstermiştir. Ayrıca model çıktıları, Çukurova içinde nispeten daha düşük rakımlı, nemli ve hava akımı sınırlı alanlarda elverişli beş günlük dönem sayısının sistematik olarak daha yüksek olduğunu; buna karşılık hafif meyilli, rüzgâr alan ve iyi drenajlı alanlarda riskin daha düşük seyrettiğini ortaya koymuştur.

4. Tartışma

Bu çalışma, Çukurova'nın erken sezon patates üretim koşullarında yaygın olarak kullanılan takvim esaslı fungisit programlarının hem ekonomik hem de çevresel açıdan uygun olmadığını ortaya koymaktadır. Sabit aralıklarla yapılan uygulamalar, enfeksiyon riskinin düşük olduğu dönemlerde gereksiz ilaçlamalara yol açarken; hava koşullarının aniden son derece elverişli hâle geldiği kısa süreli dönemlerde, yoğun inokulum baskısı altında dahi yeterli korumayı her zaman sağlayamamaktadır. Benzer sonuçlar, başta Batı Avrupa olmak üzere pek çok patates üretim bölgesinde, sabit programlı uygulamalardan tahmin uyarı sistemi temelli uygulamalara geçiş sürecinde ortaya konmuştur (Schepers, 2004; Small ve ark., 2015; Castaño-Serna ve ark.,

2025). İklim koşullarına bağlı tahmin uyarı sistemleri, *P. infestans*'ın enfeksiyon ve sporulasyonunun sıcaklık, bağıl nem ve yaprak ıslaklığına sıkı sıkıya bağımlı olması gerçeğinden yararlanmaktadır. Bu ilişkiler sayısallaştırıldığında, Blitecast, PhytoPRE, Mileos, NEGFRY ve BlightPro gibi sistemler, yüksek riskli dönemleri belirleyerek ilaçlama kararlarını optimize edebilmekte; pek çok ülkede uygulama sayısını anlamlı düzeyde azaltırken, hastalık kontrol düzeyini koruyabilmektedir (Schepers, 2004; Small ve ark., 2015; Meno ve ark., 2024). Çukurova'da elde edilen bulgular, benzer faydaların bölgesel iklim özellikleri gözetilerek yapılan kalibrasyonlarla Türkiye koşullarında da elde edilebileceğini göstermektedir.

Beş günlük yeniden enfeksiyon dönemlerine dayalı simülasyon modeli, epidemiyolojik dinamikleri verim kaybıyla doğrudan ilişkilendirmesi bakımından tahmin uyarı sistemlerine tamamlayıcı bir rol üstlenmektedir. Bu tür modeller düşük riskli yıllarda ilaçlama sıklığını azaltmada önemli avantajlar sunmaktadır (Filippov ve ark., 2018).

Çalışmanın en önemli bulgularından biri, entegre yönetim stratejisinin tek başına kimyasal mücadelenin önüne geçmesidir. Münavebe, sertifikalı tohumluk kullanımı, enfekteli artıkların uzaklaştırılması gibi kültürel önlemler, tarladaki primer inokulum yükünü azaltarak epideminin başlamasını geciktirmekte; bu da tahmin uyarı sistemi temelli fungisit uygulamalarının daha az sayıda ve daha etkin şekilde gerçekleştirilmesine olanak tanımaktadır. Bu sonuç, patates mildiyö hastalığına dayanıklı genlerin (*Solanum bulbocastanum*'dan aktarılan RB geni) devreye girdiği durumlarda da, dayanıklılığın sürdürülebilirliği açısından fungisitler ve kültürel önlemlerle entegre yönetimin gerekliliğini vurgulayan çalışmalarla paralellik göstermektedir (Song ve ark., 2003; Blossei ve ark., 2022).

Bunun yanında tahmin uyarı sistemi temelli uygulamaların üretici uygulamalarına entegrasyonu önünde bazı yapısal engeller bulunmaktadır. Bunlar arasında; tarla düzeyinde güvenilir ve gerçek zamanlı meteorolojik veri eksikliği, anlaşılabilir arayüzlere sahip uygulamaların yetersizliği, çiftçiler ve teknik personel arasında bu sistemlerin etkisi ile ilgili eğitim çalışmalarının eksikliği sayılabilir. Bu engellerin aşılması, araştırma kuruluşları, yayım birimleri, özel sektör arasında güçlü bir iş birliği gerektirmektedir (Günaçtı ve Ay, 2021; Majeed, 2017).

Türkiye özelinde, özellikle Çukurova'dan elde edilen yerel verilerin üreticilere aktarılması büyük önem taşımaktadır. Winstel, Blitecast ve Ullrich–Schrödter modellerinin Adana koşullarındaki karşılaştırmaları ve bu çalışmada sunulan tahmin uyarı destekli stratejilerin verimi düşürmeden ilaçlama sayısını azaltabildiğini somut olarak göstermektedir.

5. Sonuç ve Öneriler

Patates mildiyö hastalığı, Çukurova Bölgesi'nde özellikle erken sezon patates üretimini ciddi biçimde tehdit etmeye devam etmektedir. Mevcut üretici pratiğinde, takvim esaslı fungisit programlarına duyulan güven, yüksek üretim maliyetleri, çevresel kirlilik riskleri ve *P. infestans* popülasyonunda fungisit direnci gelişimi gibi olumsuz sonuçları da beraberinde getirmektedir. Bu çalışma, Çukurova koşullarında iklim koşullarına dayalı tahmin uyarı sistemlerinin, sabit aralıklı programlara kıyasla fungisit uygulama sayısını yaklaşık %25–30 oranında azaltabileceğini, kültürel önlemlerle desteklenen entegre yönetim stratejisinin, en düşük hastalık şiddeti ve en yüksek ekonomik getiriyi sağladığını, ortaya koymuştur. Patates mildiyö hastalığı ile mücadelede fungisitler, vazgeçilmez bir araç olmakla birlikte, her 7–10 günde bir uygulanacak girdiler olarak değil; iklim koşulları, inokulum düzeyi, çeşit dayanıklılığı ve kültürel önlemlerle birlikte dinamik şekilde optimize edilecek bir bileşen olarak ele alınmalıdır. Yerel iklim ve üretim sistemlerine uygun iklim verilerine dayalı erken uyarı sistemleri Türkiye'nin patates üretim bölgelerinde patates mildiyö hastalığı yönetim stratejilerini yeniden tanımlama ve daha sürdürülebilir bir ürün koruma anlayışı geliştirme potansiyeline sahiptir.

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USAblight ve CIP Global estimates of late blight impact and economic losses.

FUNGAL DISEASES OF POTATO (*SOLANUM TUBEROSUM* L.) AND INTEGRATED DISEASE MANAGEMENT APPROACHES

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ABSTRACT

Potato (*Solanum tuberosum* L.) is a strategic staple crop worldwide, playing a key role in food security and rural development. However, its production is severely constrained by numerous fungal diseases affecting foliage, roots, stems, and tubers, leading to substantial yield and quality losses. Major fungal pathogens include *Phytophthora infestans* (late blight), *Alternaria solani* (early blight), *Fusarium* spp. (dry rot and wilt), *Verticillium* spp. (wilt), *Rhizoctonia solani* (black scurf and stem canker), *Helminthosporium solani* (silver scurf), *Phoma exigua* var. *foveata* (gangrene), *Phytophthora erythroseptica* (pink rot), and *Sclerotinia sclerotiorum* (white mold). This review provides an integrated overview of these key fungal diseases, focusing on their taxonomy, life cycles, infection biology, epidemiology, typical symptoms, and economic impact. Furthermore, it summarizes advances in evaluates integrated disease management strategies, including resistant cultivar development, fungicide use, and biological control. Special attention is given to the status and management of major fungal diseases of potato under Turkish production conditions. The review aims to serve as a comprehensive reference for researchers, plant pathologists, and agronomists working on sustainable management of fungal diseases in potato cultivation.

ÖZET

Patates (*Solanum tuberosum* L.), dünya genelinde gıda güvenliği ve kırsal kalkınma açısından stratejik öneme sahip temel bir nişasta kaynağıdır. Ancak patates üretim; yaprak, toprak ve yumru kökenli çok sayıda fungal hastalık nedeniyle ciddi verim ve kalite kayıplarıyla karşı karşıyadır. Geç yanıklık (*Phytophthora infestans*), erken yanıklık (*Alternaria solani*), *Fusarium* türlerine bağlı kuru çürüklük ve solgunluklar, *Verticillium* solgunlukları, *Rhizoctonia solani*'nin neden olduğu siyah kabuk ve kök boğazı çürüklükleri, gümüşi leke (*Helminthosporium solani*), gangren (*Phoma exigua* var. *foveata*), pembe çürüklük (*Phytophthora erythroseptica*) ve *Sclerotinia sclerotiorum* kaynaklı beyaz çürüklük, patates üretiminde öne çıkan başlıca fungal hastalıklardır. Bu derlemede söz konusu etmenlerin taksonomik konumları, yaşam döngüleri, enfeksiyon biyolojisi, epidemiyolojisi, tipik belirtileri ve ekonomik etkileri özetlenmekte; entegre mücadele (IPM), dayanıklı çeşit ıslahı, biyolojik ve kimyasal kontrol stratejileri tartışılmaktadır. Ayrıca Türkiye'de patateste önemli olan fungal hastalıkların güncel durumu örneklendirilmekte ve gelecekteki araştırma ve hastalık yönetimi çalışmalarına yönelik öneriler sunulmaktadır. Çalışma, patates hastalıklarıyla çalışan araştırmacılar, bitki patologları ve ziraat mühendisleri için bütüncül bir başvuru kaynağı olmayı amaçlamaktadır.

1. Giriş

1.2 Patatesin Küresel Önemi ve Fungal Hastalıkların Patates Üretimindeki Rolü

Patates (*Solanum tuberosum* L.), pirinç, buğday ve mısırın ardından dünya üretiminde dördüncü sırada yer alan temel bir gıda bitkisidir. Yüksek karbonhidrat içeriği, kaliteli protein, vitamin ve mineral zenginliği ile özellikle gelişmekte olan ülkelerde enerji ve besin öğesi gereksiniminin önemli bir bölümünü karşılamaktadır. FAO verilerine göre yıllık küresel patates üretimi 370 milyon tonun üzerindedir ve Avrupa, Asya, Kuzey Amerika ile Afrika'da geniş üretim alanları bulunmaktadır.

Patates; taze tüketimin yanı sıra kızartmalık ürünler, cips, nişasta ve alkol üretimi gibi endüstriyel işleme sektörleri için de önemli bir hammaddedir. Bu nedenle, patates üretiminde karşılaşılan hastalık sorunları yalnızca tarla verimini değil, depolama, işleme ve pazarlama zincirinin tamamını etkilemektedir.

Patates; virüsler, bakteriler, nematodlar ve fungal patojenler gibi çok çeşitli biyotik etmenlere duyarlı bir türdür. Vegetatif çoğaltım nedeniyle, özellikle tohumluk materyal üzerinden pek çok hastalığın yıldan yıla taşınması söz konusudur. Fungal patojenler hem tarlada hem depoda, yeşil aksam, gövde, kök ve yumruda hastalıklara neden olarak: verim kayıplarına, kalitede bozulmaya, depolama kayıplarına, artan ilaçlama ve işçilik maliyetlerine, fungisit direnci ve çevresel riskler gibi sürdürülebilirlik sorunlarına yol açmaktadır.

Tarihsel olarak, geç yanıklık mildiyö hastalığı (*Phytophthora infestans*) İrlanda Patates Kıtlığı gibi sosyo-ekonomik felaketlerle anılmakta; günümüzde de pek çok ülkede sezonda 10–20'ye, tropik bölgelerde 20–30'a varan fungisit uygulaması gerektiren en önemli patates hastalığı olmaya devam etmektedir. Benzer şekilde; *Alternaria sp.*, *Fusarium sp.*, *Verticillium sp.*, *Rhizoctonia solani* ve *Sclerotinia* spp, hem primer hastalık etmeni hem de sekonder yara paraziti olarak patates üretim zincirinin farklı aşamalarında ciddi sorunlar oluşturmaktadır.

2. Patates Fungal Patojenlerinin Genel Özellikleri Taksonomi ve Patojen Çeşitliliği

Patatesi enfekte eden patojenler farklı şube ve sınıflara dağılmış durumdadır:

Oomycetes

Phytophthora infestans (Mildiyö-Geç yanıklık),

Phytophthora erythroseptica (Pembe çürüklük)

Ascomycetes

Alternaria solani (Erken yanıklık),

Fusarium spp. (Kuru çürüklük, Solgunluk),

Verticillium dahliae, V. albo-atrum (Solgunluk),

Sclerotinia sclerotiorum (Beyaz çürüklük),

Helminthosporium solani (Gümüşi Leke),

Phoma spp. (Gangren) gibi türleri içerir.

Basidiomycetes

Rhizoctonia solani (Siyah siğil hastalığı) bu grupta önemli bir patojendir.

Bu geniş yelpaze, patatesin hem toprak kaynaklı hem de hava kaynaklı birçok farklı hastalık etmenine açık olduğunu göstermektedir. Farklı taksonomik gruplara mensup olmalarına

rağmen, bu patojenler arasında bazı ortak özellikler dikkat çeker: Toprakta, bitki artıkları veya yumru yüzeyinde sklerot, klamidospor, piknidyum, sporangium gibi dayanıklı yapılarla uzun süre canlı kalabilme, uygun sıcaklık ve nem koşullarında çoğunlukla çok kısa sürede büyük spor populasyonları oluşturarak hızlı epidemilere yol açma, enfeksiyon için yaprak yüzeyinde serbest su, yüksek bağıl nem, uygun sıcaklık aralıkları ve çoğu zaman da yaralanma veya doğal açıklıklardan giriş gereksinimi, polifag patojenler olmaları gibi biyolojik özellikler, hem hastalıkların epidemiyolojisini hem de uygulanacak mücadele stratejilerini (münavebe, dayanıklı çeşit, fungisit seçimi vb.) doğrudan etkilemektedir

3. Patates Tarımında Sorun Olan Fungal Hastalıklar

3.1 Geç Yanıklık – Patates Mildiyö Hastalığı (*Phytophthora infestans)*

Patates Mildiyö hastalığı, patatesin en yıkıcı hastalıklarından biridir. Etmen, Oomycetes sınıfında yer alan *P. infestans* olup sporangium ve zoosporlar aracılığıyla yayılır. Bulaşık tohumluk yumrular, tarlada kalan enfekteli bitki artıkları ve uygun iklim koşulları (15–20 °C, yüksek bağıl nem) epidemilere neden olan temel faktörlerdir. Hastalık belirtileri, yapraklarda suyla ıslanmış gibi başlayan düzensiz lekeler kısa sürede kahverengileşir, lezyon kenarlarında özellikle nemli havalarda beyaz-gri bir sporlanma halkası görülür. İlerlemiş dönemlerde hızla birleşerek geniş nekrotik alanlara ve erken bitki ölümüne neden olur. Yumrularda kabuğun hemen altında kahverengi, sert çürüklük ve iç dokuda bozulma tipik belirtilerdir (Gunacti et al., 2019). Uygun koşullarda kontrolsüz bırakıldığında mildiyö nedeniyle %80–100'e varan verim kayıpları bildirilmiştir. Ayrıca depoda sebep olduğu yumru çürüklükleriyle pazar kaybını artırır. Hastalıkla Mücadelede; dayanıklı veya kısmi dayanıklı çeşitlerin kullanımı, sertifikalı ve sağlıklı tohumluk yumru temini, tarlada enfekteli bitki artıkları ve konukçu yabancı otların yok edilmesi, tahmin uyarı sistemleri ile zamanlanmış fungisit uygulamaları, Metalaksil, fluazinam, mandipropamid vb. fungisitlerin rotasyonlu ve direnç yönetimine uygun kullanımı (Cooke et al., 2012; Fry, 2016; Gunacti et al.,2021) önerilmektedir.

3.2. Erken Yanıklık (*Alternaria solani)*

Alternaria solani, nekrotrofik bir patojen olup özellikle sıcak ve nispeten kurak koşullarda hastalık şiddeti artar. Hastalık belirtileri, alt yapraklardan başlayan, ortasında konsantrik halkalar bulunan kahverengi lekeler tipiktir. İlerlemiş enfeksiyonlarda yapraklar sararıp kurur; bitkinin fotosentez yapma kapasitesi önemli ölçüde azalır. Hastalık nedeniyle iklim ve yetişme koşullara bağlı olarak %20–80 arasında değişen verim kayıpları rapor edilmiştir (Rotem, 1994; Leiminger et al., 2014). Hastalıkla mücadede genellikle fungisit kullanımı öne çıkmaktadır. Bunun yanında dengeli azot gübrelemesi ve stres koşullarının azaltılması, enfekteli artıkların yok edilmesi ve ekim nöbeti, Azoksistrobin, difenokonazol gibi fungisitlerin direnç yönetimi ilkelerine uygun kullanımı, biyolojik mücadele ve indüklenmiş direnç çalışmaları, son yıllarda artan önem taşımaktadır.

3.3 Fusarium Kaynaklı Kuru Çürüklük ve Solgunluklar (*F. solani, F. oxysporum*)

Fusarium spp. (*F. solani, F. oxysporum*), toprak ve yumru kaynaklı önemli patojenlerdir. Hem depolama döneminde kuru çürüklük hem de tarlada vasküler solgunluk şeklinde ortaya çıkabilirler. Klamidospor ve dayanıklı hifler şeklinde toprakta uzun süre canlı kalabilirler. Enfeksiyon genellikle hasat veya ekim sırasında oluşan yaralardan gerçekleşir. Uygun koşullarda (25–28 °C, geniş pH aralığı) sporlar hızla çimlenir. Hastalık, yumrularda kuru, çökük, koyu renkli çürük alanlar ve iç dokuda lifli, kuru doku bozulması şeklinde belirtilere neden olur. Solgunluk tablolarında ise bitki alt kısmından başlayan sararma, solma ve iletim demetlerinde kahverengileşme tipiktir. Mücadele yöntemi olarak hasat ve taşıma sırasında yaralanmaların en aza indirilmesi, uzun süreli ekim nöbeti ve toprak sağlığının iyileştirilmesi,

sağlıklı tohumluk kullanmak tohum ilaçlaması yapmak ve uygun depolama koşulları sağlamak önemlidir.

3.4. Verticillium Solgunluğu (*Verticillium dahliae* ve *V. albo-atrum)*

Verticillium spp, ksilem dokusunu kolonize eden toprak kökenli patojenlerdir. Mikrosklerot yapıları sayesinde toprakta yıllarca canlı kalabilirler. İlk hastalık belirtileri, alt yapraklarda kloroz ve hafif solgunluk olarak ortaya çıkar; daha sonra tüm bitkiye yayılarak ciddi bir gelişme geriliği ve erken yaşlanmaya yol açar. İç kesitte iletim demetlerinde belirgin kahverengi-siyah renk değişimi izlenir. Hastalıkla mücadelede; dayanıklı veya toleranslı çeşitlerin kullanımı, uzun süreli münavebe, solarizasyon, organik materyal ilavesi ve toprak sağlığını güçlendiren uygulamalar, drenaj ve sulama yönetiminin iyileştirilmesi önerilmektedir (Rowe et al., 1987; Powelson & Rowe, 1993).

3.5. Rhizoctonia Siyah Siğil Hastalığı (*Rhizoctonia solani)*

R. solani, patateslerde siyah kabuk (tuber yüzeyinde siyah sklerotlar) ve kök boğazı/kök çürüklüğü ile karakterize edilen çok önemli bir toprak patojenidir. Hastalığın en tipik belirtisi, yumru yüzeyinde sert, siyah, soyulduğunda kabuğu bozmayan sklerot kitleleri, gövdede kök boğazında ve köklerde çökük, kahverengi lezyonların görülmesidir. Enfeksiyon ilerledikçe zayıf kök sistemi, bodur gelişme, alt yaprakların sararması ve ileri durumlarda bitki ölümü görülebilir. Hastalık şiddeti, ılık ve nemli toprak koşullarda, yetersiz drenaj, ağır bünyeli topraklar ve sık sulama koşullarında artış gösterir. Hastalıkla mücadelede sağlıklı, temiz tohumluk kullanımı çok önemlidir. Tohum ilaçlaması (carboxin, pencycuron vb.) en çok kullanılanı yöntemdir. Son yıllarda, biyolojik mücadele etmenleri (*Trichoderma* spp., *Bacillus subtilis* vb.) ile kombine entegre yöntemler hastalıkla mücadelede başarı sağlamıştır (Mishra et al., 2000; Tsror et al., 2001).

3.6. Gümüşi Leke (*Helminthosporium solani)*

Gümüşi leke, özellikle depolama aşamasında problem oluşturan yüzey patojenidir. Yumru yüzeyinde gümüşi-parlak lekeler ve kabukta renk açılması ile karakterizedir. Yüksek nem ve yetersiz havalandırma, hastalık gelişimini hızlandırır (Christ, 1998; Peters et al., 2008). Sağlıklı tohumluk kullanmak, depoda sıcaklık ve nem kontrolü, iyi havalandırma koşullarının sağlanması hastalığı önler. Uygun depolama öncesi yumru fungisit uygulamaları da mücadelede tercih edilmektedir.

3.7. Gangren (*Phoma exigua var. foveata)*

Phoma exigua var. foveata başta olmak üzere *Phoma* türleri, depolama döneminde yumrularda çökük nekrotik lekeler ve iç dokuda bozulma ile karakterize gangrene neden olur Mücadelede, hasatta yumru yaralanmalarının azaltılması, uygun depolama sıcaklığı ve nem yönetimi, tohumluk yumruların fungisitlerle (benomil, tiabendazol vb.) muamelesi önerilmektedir (Hide & Cayley, 1983; Peters et al., 2005).

3.8. Beyaz Çürüklük *(Sclerotinia sclerotiorum*)

S. sclerotiorum, geniş konukçu dizisine sahip, sklerot oluşturan bir patojendir. Nemli ve serin koşullarda gövde, yaprak ve yumruya yakın dokularda su içeriği yüksek, yumuşak çürüklüklerle birlikte pamuksu, beyaz misel gelişimi tipiktir. Dokuların içinde siyah, sert sklerotlar oluşur. Münavebe ve konukçu olmayan bitkilerle rotasyon, drenajın geliştirilmesi, yoğun sulamadan kaçınılması önerilen kültürel mücadele yöntemleridir.

3.9.Diğer Önemli Hastalıklar

Patates siğil hastalığı (*Synchytrium endobioticum*), tozlu kabuk (*Spongospora subterranea*), skin spot (*Polyscytalum pustulans*) ve kömür çürüklüğü (*Macrophomina phaseolina*) gibi etmenler de gerek tarlada gerek depoda bölgesel ve dönemsel olarak önem kazanabilmektedir. Bu hastalıklarda da temel strateji; karantina önlemleri, dayanıklı çeşit kullanımı, toprağın ve depolama koşullarının iyileştirilmesi ve uygun fungisit uygulamalarıdır.

4. Sonuç ve Tartışma

Patates üretiminde fungal hastalıklar hem verim hem de kalite açısından küresel ölçekte ciddi kayıplara neden olmakta; bulaşık tohumluk, uygun iklim ve yetersiz mücadele koşullarında epidemi riskini sürekli canlı tutmaktadır. Sonuç olarak, fungal patojenlerin gelişimi ve hastalık epidemilerinin şiddeti, iklim koşulları ve tarımsal uygulamalarla yakından ilişkilidir. Yüksek bağıl nem, uzun yaprak ıslaklığı süreleri ve patojen için uygun sıcaklık aralıkları, özellikle geç yanıklık, erken yanıklık ve *Sclerotinia sp* kaynaklı çürüklükler gibi hastalıkların görülmesine yol açarken, toprak sıcaklığı ve nem düzeyi *Rhizoctonia solani, Fusarium* spp.ve *Verticillium* spp. kaynaklı sorunları etkilemektedir. Türkiye'de Karadeniz'in nemli ve serin koşulları geç yanıklık ve bazı depolama çürüklükleri için uygun ortam oluştururken, İç Anadolu ve Doğu Anadolu'da daha çok erken yanıklık, toprak kökenli solgunluklar ve *Rhizoctonia* kaynaklı problemler öne çıkmaktadır. Bölgesel çalışmalarda, geç yanıklığın bazı yıllarda %50'ye varan verim kayıplarına neden olabildiği; erken yanıklık ve gümüşi lekenin ise özellikle ihraç edilecek ve sofralık yumrularda ciddi kalite kaybı yaratabildiği bildirilmektedir. Farklı ekolojik bölgeleri barındıran ülkelerde, geç yanıklık, erken yanıklık, gümüşi kabuk, toprak kaynaklı solgunluklar ve depolama çürüklükleri gibi hastalıklar, bölgelere göre değişen ağırlıkta ortaya çıkmaktadır.

Sürdürülebilir patates üretimi için: Entegre mücadele yaklaşımının tüm bileşenleriyle (kültürel, kimyasal, biyolojik, genetik) uygulanması, dayanıklı çeşitlerin geliştirilmesi ve kullanımının yaygınlaştırılması, fungisit direncinin düzenli olarak izlenmesi, büyük önem taşımaktadır. Gelecek araştırmaların; patojen popülasyon dinamikleri, iklim değişikliğinin hastalık epidemiyolojisine etkisi, mikrobiom temelli toprak sağlığı yaklaşımları ve üretici odaklı dijital karar destek sistemleri üzerine yoğunlaştırılması, patates fungal hastalıklarının yönetiminde yeni ufuklar açacaktır.

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EFFECT OF CALCIUM-BASED SOIL AND FOLIAR AMENDMENTS ON THE CHEMICAL COMPOSITION OF 'CARDINAL' GRAPEVINE LEAVES, SHOOTS, AND BERRIES

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ABSTRACT

This study evaluated the effects of calcium-based soil improvers of natural and ecological origin on the chemical composition of leaves, shoots, and grapes of the *Vitis vinifera* L. cultivar 'Cardinal' grown in the Skopje vineyard region, North Macedonia. These calcium products, rich in calcium and magnesium, were applied both as soil amendments and foliar fertilizers to enhance plant nutrition. The experimental design consisted of five treatment variants: 1) Control (untreated), 2) Zeofit Forte at 3 g/L, 3) Zeofit Forte at 5 g/L, 4) Zeofit Plus at 3 g/L, and 5) Zeofit Plus at 5 g/L. Foliar applications were conducted four times during the growing season: 15 days before flowering, 15 days after flowering, during the berry growth phase, and at the onset of veraison. Chemical analyses showed significant increases in key quality parameters, including total phenolics, flavonoids, vitamin C, carbohydrates, and total acids, in all treated variants compared to the control. The most notable improvements were recorded in Variants 2 and 4, where lower concentrations of foliar fertilizers were applied. These results suggest that calcium-based soil improvers combined with foliar fertilization can positively influence the biochemical composition and overall quality of 'Cardinal' grapes. This study highlights the importance of integrating natural calcium amendments and foliar treatments in vineyard management to improve grape nutritional value while supporting sustainable agricultural practices.

Keywords: Grapevine production, foliar fertilizing, fertilizer concentration.

INTRODUCTION

Grapevine (*Vitis vinifera* L.) is one of the most widely cultivated and economically important fruit crops globally, renowned for its high nutritional value, distinctive flavor profile, and considerable profitability (Huang et al., 2023; Jiang et al., 2024). Owing to these attributes, grapes have achieved remarkable popularity worldwide.

The Republic of North Macedonia offers nearly ideal natural conditions for grapevine cultivation and the production of high-quality wines. This is largely due to its favorable geographic position as a sunny and mountainous country, characterized by a Mediterranean–continental climate with warm, sunny days and cool nights.

Grapes are among the most appreciated fruits globally, valued for their taste, aroma, and nutritional richness. They are consumed fresh or processed into juice, wine, raisins, and jam, and are considered one of the highest-quality fruits for consumption. Beyond direct consumption, grapes are also widely used as raw material for the production of grape seed oil, anthocyanins, tannins, ethanol, and other value-added products. Their composition includes a broad spectrum of beneficial nutrients—vitamins (A, B, C, E, and P), minerals, carbohydrates, lipids, proteins, and polyphenolic compounds—distributed throughout the skin, seeds, and pulp. Additionally, grapes contain sugars primarily in the form of monosaccharides (glucose and fructose), as well as various phenolic compounds (Kandylis et al., 2021; Li et al., 2020; James et al., 2022).

Nutrient management is a key factor in maximizing grape quality and yield, as well as bridging the gap between actual and potential productivity. While essential nutrients are naturally present in the soil and are absorbed by plant roots, their excessive availability can lead to overly vigorous vegetative growth, resulting in dense canopies that overly shade the fruit or cause nutrient toxicity. Conversely, nutrient depletion over time necessitates the replenishment of soil reserves through the application of organic and/or mineral fertilizers to sustain yield and improve grape quality (James et al., 2022).

Grapevines require substantial nutrient input, and their growth, productivity, and fruit quality are closely linked to the availability of essential macro- and micronutrients. Although grape production has often relied on inorganic fertilizers, excessive use of such inputs can degrade soil health and negatively impact the environment (Vijayalakshmi et al., 2022).

While nutrient supplementation can address deficiencies, excessive concentrations may lead to toxic effects, adversely impacting grapevine performance and the quality of the grapes and their derived products (Serrano et al., 2017). Therefore, the rational application of fertilizers is necessary to achieve sustainable grapevine productivity and quality.

Fertilization is one of the most critical agro-technical practices in viticulture, with a significant influence on grape yield and quality (Delgado et al., 2004). By implementing modern agro-technical approaches, particularly with optimized fertilization strategies—timed appropriately and tailored to the phenological stages of vine development—it is possible to enhance grapevine growth and ensure the production of premium-quality grapes (Stojanova, 2023).

As a perennial crop, grapevine requires large quantities of nutrients, which are utilized differently across various developmental phenophases. Soil-based fertilization alone often proves inadequate, due to limited nutrient availability caused by unfavorable soil physical properties or drought stress (Stojanova, 2019). Therefore, foliar nutrition plays a vital role in successful grapevine cultivation and the production of high-quality grapes.

Nowadays, foliar nutrient application is widely adopted as a supplementary practice in plant production. Nutrients applied through foliar sprays can be absorbed via stomata, the cuticle, trichomes, veins, and other modified epidermal structures such as lenticels (Fernández et al., 2013; Fernández et al., 2021). This method of nutrient delivery offers both economic and environmental advantages, as it allows for more efficient nutrient uptake by targeting critical growth stages such as bud break, flowering, and fruit set (Gautier et al., 2018).

Foliar nutrition enables a preventive approach during phenophases when nutrient demand is high but root uptake is limited. This additional feeding through the leaves contributes significantly to cluster development and grape quality (Stojanova, 2018; Colapietra and Alexander, 2006). Furthermore, foliar fertilization enhances nutrient uptake efficiency by avoiding common soil-related limitations, such as antagonistic interactions between elements, nutrient fixation, and the formation of unavailable nutrient compounds (Stojanova, 2018; Stojanova et al., 2024b).

One of the major advantages of foliar fertilization is its rapid effect, with the flexibility of multiple applications during the growing season, resulting in a wide range of beneficial outcomes (Stojanova, 2018; Stojanova et al., 2024c).

A balanced combination of soil and foliar fertilization is fundamental for achieving both high yield and fruit quality. The optimal uptake of macro- and micronutrients by the grapevine directly influences key physiological and biochemical processes that govern its growth, development, and fruiting potential (Stojanova et al., 2024a).

The present research aimed to assess the impact of soil fertilization and different concentrations of foliar fertilization on the chemical composition of leaves, grape clusters, and berries in the *'*Cardinal*'* grapevine cultivar, grown under the specific climatic and edaphic conditions of the Skopje vineyard region in North Macedonia.

MATERIALS AND METHOD

Experimental design

The investigations were conducted in a vineyard located in the Skopje vineyard district, North Macedonia. The subject of the study was the 'Cardinal' grapevine variety, cultivated in a vineyard that was in the full bearing phase. The grapevines were planted at a spacing of 2.8 × 1.0 m, corresponding to a planting density of 3,571 vines per hectare. The cultivation system employed was a trellis training system, with a trunk height maintained at 70 cm.

During the basic autumn soil preparation, the vineyard was fertilized with a complex NPK 10-20-30 fertilizer at a rate of 500 kg/ha. Soil fertilization was carried out by applying the fertilizer into previously opened furrows, placed at a depth of 40 cm and at a distance of 60 cm from the vine trunks.

The field experiment was established under drip irrigation conditions. Throughout the vegetation period, all standard agricultural and ampelotechnical practices were applied to maintain the vineyard in optimal condition.

The experiment included five treatment variants, each set up with three replications. The experimental variants were as follows:

1. Control (untreated);

2. Zeofit forte (SiO_2 15%, CaO 35%, MgO 7%, P_2O_5 0.04%, K_2O 0.63%, MnO 0.043%, Fe_2O_3 4.70%) – 3 g/L;

3. Zeofit forte (SiO_2 15%, CaO 35%, MgO 7%, P_2O_5 0.04%, K_2O 0.63%, MnO 0.043%, Fe_2O_3 4.70%) – 5 g/L;

4. Zeofit plus (SiO_2 25%, CaO 21%; MgO 13%; K_2O 1.1%; Fe_2O_3 2.0%) – 3 g/L;

5. Zeofit plus (SiO_2 25%, CaO 21%; MgO 13%; K 1.1%; Fe_2O_3 2.0%) – 3 g/L.

Each treatment variant included 10 grapevines, amounting to a total of 150 grapevines across all experimental plots. The treatments involved foliar application of a tested fertilizer solution at concentrations of 3 g/L and 5 g/L. A total of four foliar treatments were performed during the vegetation period, applied at key phenological stages: 15 days before flowering, 15 days after flowering, during the berry growth phase, and at the onset of veraison. The foliar sprays were applied manually using a hand-held sprayer, targeting the leaf surfaces for optimal nutrient absorption.

Zeofit Forte and Zeofit Plus are soil conditioners of natural origin, categorized as fully ecological products. Due to their high content of calcium and magnesium, these materials are also effective when used for foliar nutrition. Their application has been shown to stimulate flowering, enhance plant immunity, and contribute to increased yields.

Plant Material – Grapevine Cultivar

The grapevine cultivar used in this research was *'Cardinal'*, a variety developed in California through the hybridization of the *Flame Tokay* and *Ribier* cultivars. Today, *'Cardinal'* is widely cultivated across the globe, with significant presence in countries such as Spain, Italy, Romania, and Mexico. It performs particularly well in regions that are characterized by dry weather during the ripening period and where there is no risk of severe frost during winter (Popovic et al., 2020).

The grape clusters are large, weighing between 250 and 550 g, and exhibit an elongated shape with an amber-yellow coloration. The berries may appear loosely or moderately clustered. In North Macedonia, *'Cardinal'* is primarily grown in the warmer viticultural zones. It is a late-ripening cultivar, with harvest typically occurring from late September to early October. Under cold and rainy conditions during the flowering phase, the clusters may develop a reddish hue.

Soil Sampling and Agrochemical Analysis

To assess the soil's fertility status prior to the establishment of the experiment, composite soil samples were collected from three depth intervals: 0–30 cm, 30–60 cm, and 60–80 cm (Stojanova, 2019). In the laboratory, the soil samples were air-dried and processed for agrochemical analysis. The following parameters were determined using standard methodologies:

- Soil pH – determined potentiometrically using a pH meter (Stojanova, 2017);

- Available nitrogen (easily mineralizable) – determined by the Tjurin and Kononova method (Stojanova, 2017);

- Available phosphorus – determined by the AL method with spectrophotometric reading (Stojanova, 2017);

- Available potassium – also determined using the AL method and spectrophotometric analysis (Stojanova, 2017);

- Humus content – assessed using the potassium permanganate method by Kotzman (Stojanova, 2017);

- Carbonate content – determined by the Scheibler calcimetric method (Stojanova, 2017).

Harvesting Procedure

The grape harvest was performed at the stage of full technological maturity, separately for each treatment variant and replication. Grapes were collected manually to preserve the integrity of the clusters and ensure sample accuracy.

Sampling and Chemical Analysis of Leaves and Clusters

Following the harvest, during the period of highest macro- and micronutrient stability, leaf samples were collected to determine their chemical composition. The sampling was performed using the lower leaves situated opposite the first grape cluster, taken from all sides of the vine to obtain a representative sample.

In the laboratory, the leaves were first washed in a 0.05% HCl solution, then rinsed with distilled water and air-dried at room temperature. A total of 20 leaves per variant and per replication were collected and prepared for analysis.

Samples of one-year-old mature shoots (canes) were taken in November, with each average sample consisting of material from 10 individual grapevines per treatment variant. The shoots were ground into a fine powder using an electric mill and prepared for chemical analysis.

In both leaf and shoot samples, the following elements were determined:

- Nitrogen (N) – determined by the Kjeldahl method (Stojanova, 2017);
- Phosphorus (P_2O_5) – analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES) (Stojanova, 2017);
- Potassium (K_2O) – measured after incineration with concentrated H_2SO_4 and detection using a flame photometer (Stojanova, 2017);
- Calcium (Ca), Magnesium (Mg), Iron (Fe), Manganese (Mn), Boron (B), Zinc (Zn), and Molybdenum (Mo) – determined by ICP-AES (Sarić et al., 1989).

Chemical Analysis of Grape Berries

Following harvest, 10 grape clusters per treatment and replication were sampled. For the average sample, clusters were selected based on dry matter content, measured with a hand-held refractometer using juice from several berries. In laboratory conditions, berries were manually separated from the rachis and prepared for analysis (Stojanova, 2017).

The following chemical parameters were determined in the grape berries:

- Total phenolic content (TP) – determined using modified method of Stojanova et al. (2021);
- Total flavonoid content (TF) – determined using modified method of Stojanova et al. (2021);
- Vitamin C content – determined using the Muri method (Stojanova, 2017);
- Total carbohydrate content – determined using modified method of Masuko et al. (2005);
- Total acid content – determined using modified method of Stojanova et al. (2017);

Statistical analysis

The experimental data were subjected to statistical analysis using the software package SPSS version 20.0. In order to evaluate the presence of statistically significant differences among the treatment variants, a one-way analysis of variance (ANOVA) was performed. Where significant differences were detected, Tukey's HSD post hoc test was applied for mean separation at a significance level of $p<0.05$.

RESULTS AND DISCUSSION

Soil conditions

Soil represents a critical ecological factor that directly or indirectly influences the vital functions of grapevines. Optimal soils for viticulture are characterized by being loose, deep, and having a slightly acidic to slightly alkaline reaction. Such soils should warm up easily, provide good aeration, retain adequate moisture and nutrients, possess a lighter mechanical composition, and exhibit high microbiological activity. The concentration of various macro- and micronutrients is also pivotal in determining the soil's suitability for grape cultivation (Stojanova, 2023).

The data presented in Table 1 indicate that the analyzed soil samples can be classified as moderately fertile with respect to available nitrogen, which was measured at 6.30 mg/100 g soil. Phosphorus availability was found to be at a medium fertility level, with an average content of 14.83 mg/100 g soil across the 0–80 cm depth profile. Potassium content was classified as good, averaging 23.53 mg/100 g soil.

However, in terms of humus content, the soil was found to be poorly fertile, with an average humus concentration of 1.43% within the same depth range. The calcium carbonate content indicated that the soil is slightly calcareous, with an average value of 2.23%. The pH measurements showed that the soil reaction is neutral, creating favorable conditions for the successful growth, development, and fruiting of the grapevine.

Table 1. Agrochemical analysis of soil

Cultivar	Depth (cm)	pH		Available (mg/100g soil)			Humus (%)	$CaCO_3$ (%)
		H_2O	KCl	N	P_2O_5	K_2O		
'Cardinal'	0–30	7.55	7.25	7.10	13.80	25.00	1.40	2.50
	30–60	7.40	7.20	6.50	17.50	23.20	1.50	2.30
	60–80	7.42	7.22	5.30	13.20	22.40	1.38	1.90
	Average 0-80	**7.46**	**7.22**	**6.30**	**14.83**	**23.53**	**1.43**	**2.23**

Effect of foliar fertilizing on the chemical content of leaves and clusters

Macronutrients are fundamental elements that significantly influence grapevine growth, grape yield, and ultimately the quality of wine. Currently, monitoring nutrient status through plant tissue or soil sampling followed by chemical analysis provides crucial information on whether nutrient levels are deficient, adequate, excessive, or toxic (Debnath et al., 2021). Among these, nitrogen (N) and potassium (K) are highly mobile nutrients that can be rapidly translocated from older leaves to younger leaves or fruiting tissues when demand exceeds supply from the soil, potentially causing symptoms such as chlorosis and necrosis (Jegadeeswari et al., 2020; Michopoulos and Solomou, 2019).

Furthermore, supplementation with magnesium (Mg) and calcium (Ca) fertilizers plays a vital role in enhancing crop yields, especially when the efficiency of conventional NPK fertilizers is limited. Calcium ranks as the third most abundant nutrient available in soils and is essential for numerous plant functions (Pessoca et al., 2021).

Magnesium is a crucial macronutrient for plant growth, playing a central role throughout the plant's life cycle. It is a key constituent of the chlorophyll molecule, necessary for photosynthesis (Meng et al., 2023). Besides its role in photosynthesis, magnesium activates enzymatic processes vital for carbohydrate synthesis in leaves. Additionally, elevated magnesium levels can influence potassium uptake due to competitive interactions within the plant (Zlamalova et al., 2016). For instance, foliar application of magnesium sulfate ($MgSO_4$) at a rate of 3.86 kg Mg/ha was shown to increase grape yield by 11.2% compared to untreated controls, although other parameters were not significantly affected (James et al., 2022).

Calcium contributes significantly to fruit firmness by interacting with cell walls, binding pectin, and forming bridges between pectic acid molecules. It is an essential nutrient involved in both structural and signaling functions in plants. Absorbed by roots from the soil solution, calcium is transported via the xylem to shoots. However, its mobility within the plant is generally low, resulting in accumulation primarily in mature tissues despite the high demand of actively growing organs such as young leaves, flowers, and fruits (Garde-Cerdán et al., 2023). Calcium deficiency has been associated with several physiological disorders, including incomplete flowering, development of densely branched and shortened roots, chlorosis, and necrosis (Duan et al., 2022).

As shown in Table 2, all variants treated with different concentrations of foliar fertilizers exhibited significantly higher ($p < 0.05$) values for the analyzed chemical parameters in leaves and clusters compared to the untreated control.

Table 2. Macroelements composition of grapevine leaves from *'*Cardinal*'* variety (% of dry matter)

Variant	n	N	P_2O_5	K_2O	CaO	MgO
		$\bar{x} \pm SD$	$\bar{x} \pm SD$	$\bar{x} \pm SD$	$\bar{x} \pm SD$	$\bar{x} \pm SD$
1	20	2.20 ± 0.05^a	1.67 ± 0.16^a	1.22 ± 0.08^a	2.20 ± 0.11^a	0.41 ± 0.08^a
2	20	2.28 ± 0.08^b	1.73 ± 0.18^b	1.35 ± 0.08^b	2.52 ± 0.19^b	0.61 ± 0.13^b
3	20	2.35 ± 0.11^c	1.88 ± 0.16^c	1.53 ± 0.14^c	2.10 ± 0.05^c	0.55 ± 0.11^c
4	20	2.48 ± 0.02^d	1.95 ± 0.07^d	1.75 ± 0.05^d	2.31 ± 0.03^d	0.49 ± 0.12^d
5	20	2.43 ± 0.02^e	1.90 ± 0.01^e	1.38 ± 0.07^e	2.28 ± 0.07^e	0.50 ± 0.09^a

$^{a, b, c}$ – values for the same parameter of the different variants marked with different letters have statistically significant differences ($p<0.05$), ANOVA, *post hoc* Tukey's test.

The highest average concentrations of nitrogen (2.48%), phosphorus (1.95%), and potassium (1.75%) in the leaves were observed in variant 4, with statistically significant differences ($p < 0.05$). Additionally, the greatest average levels of calcium (2.52%) and magnesium (0.61%) in leaves were recorded in variant 2.

The combined application of soil fertilization along with varying concentrations of foliar fertilization exerted a positive impact on the content of macronutrients in the clusters of the 'Cardinal' grapevine variety. At all tested foliar fertilizer concentrations, the clusters exhibited significantly higher ($p < 0.05$) levels of the analyzed elements compared to the untreated control. Specifically, variant 4 showed the highest concentrations of nitrogen (0.96%),

phosphorus (0.65%), and potassium (0.95%) in the clusters, while variant 2 presented the greatest levels of calcium (1.53%) and magnesium (0.68%) (Table 3).

Table 3. Macroelements composition of grapevine clusters from *'Cardinal'* variety (% of dry matter)

Variant	n	N	P_2O_5	K_2O	CaO	MgO
		$\bar{x} \pm SD$	$\bar{x} \pm SD$	$\bar{x} \pm SD$	$\bar{x} \pm SD$	$\bar{x} \pm SD$
1	10	0.61 ± 0.09^a	0.37 ± 0.06^a	0.55 ± 0.09^a	1.17 ± 0.11^a	0.42 ± 0.07^a
2	10	0.89 ± 0.11^b	0.51 ± 0.16^b	0.76 ± 0.12^b	1.53 ± 0.10^b	0.68 ± 0.07^b
3	10	0.74 ± 0.07^c	0.45 ± 0.18^b	$0,90 \pm 0.12^c$	1.22 ± 0.11^c	0.45 ± 0.19^c
4	10	0.96 ± 0.16^d	0.65 ± 0.13^c	0.95 ± 0.09^d	1.48 ± 0.07^d	0.51 ± 0.06^d
5	10	0.81 ± 0.07^e	0.52 ± 0.11^d	0.69 ± 0.05^a	1.40 ± 0.09^e	0.60 ± 0.11^d

$^{a, b, c}$ – values for the same parameter of the different variants marked with different letters have statistically significant differences ($p<0.05$), ANOVA, *post hoc* Tukey's test.

In the study conducted by Bai et al. (2024) on the grape variety Queen Nina (*Vitis vinifera* L.), four foliar magnesium treatments were tested at concentrations of 1 mM (M1), 2 mM (M2), 3 mM (M3), and 4 mM (M4). The foliar application of magnesium fertilizer significantly enhanced both the dry weight and leaf area in all treatments. Among them, the M3 treatment showed the most pronounced effect compared to the others. Specifically, compared to the control (CK), the dry weight and leaf area in the M3 treatment increased by 35.9% and 37.2%, respectively ($p < 0.05$). Furthermore, the yields of M1, M2, and M3 treatments increased by 8.2%, 32.3%, and 29.1% ($p < 0.05$), respectively, relative to the control variant.

Wang et al. (2023) investigated the Merlot grapevine variety and reported nitrogen content ranging from 19.13 to 30.13 $mg \cdot g^{-1}$. In the fruit, the lowest and highest average calcium contents were observed at the MS (16.76 $mg \cdot g^{-1}$) and FBS (20.25 $mg \cdot g^{-1}$) developmental stages, respectively. Magnesium content in fruit declined during fruit development, while the opposite trend was noted in the petiole. Leaf magnesium content peaked at the VS stage with 4.1 $mg \cdot g^{-1}$, followed by the FBS and MS stages.

Mineral elements represent a vital nutritional foundation for growth and development, with appropriate nutrient supply being critical to achieving optimal fruit tree yields and quality. Zhu Xiaoping et al. (2008) analyzed nutrient content in Cabernet Sauvignon leaves without deficiency symptoms, establishing standard nutrient concentration ranges as follows: nitrogen (10.3–17.3 mg/g), phosphorus (3.1–5.4 mg/g), potassium (22.7–29.1 mg/g), calcium (6.4–11.4 mg/g), and magnesium (2.8–4.1 mg/g).

Tong et al. (2021) employed the DRIS method to explore the relationship between mineral nutrients and yield in Cabernet Sauvignon leaves. Their findings defined the diagnostic criteria for leaf nutrients in high-yield vineyards as: nitrogen (16.5–37.5 mg/g), phosphorus (2.6–6.2 mg/g), potassium (10.2–24.2 mg/g), calcium (5.6–77.3 mg/g), and magnesium (2.3–12.7 mg/g).

Calzarano et al. (2023) observed that all fertilizer applications, particularly those involving microelements, intensified foliar symptom expression. Greater vegetative growth was only detected in grapevines treated with NPK fertilizers. Notably, symptom escalation was consistently linked to a decrease in calcium, and to a lesser extent magnesium, in the leaves, supporting the hypothesis that calcium plays a critical role in the plant's defense response through a hypersensitive reaction during foliar symptom development. Despite fertilizer treatments, the vineyards remained in nutritional balance.

Effect of foliar fertilizing on the chemical content of grapes

The quality of grapes is primarily assessed by biochemical components such as total soluble solids, sugar-acid ratio, and acidity (Vijayalakshmi et al., 2022). Grapes are among the most important fruits worldwide and are rich in a variety of phenolic compounds (Crupi et al., 2016). These phenolic compounds, which rank third in abundance in grapes after carbohydrates and acids (Stojanova et al., 2024), are especially significant due to their pronounced biological activities. They exhibit strong antimutagenic, anti-inflammatory, antiallergic, and antimicrobial effects, which greatly enhance the value of grapes and their derived products.

Vitamin C (ascorbic acid) is another crucial and extensively studied component in grape berries. It plays a vital role in the redox metabolism within plant tissues, thereby increasing the plant's resistance to infections and low temperatures.

Table 4. Biochemical Parameters of 'Cardinal' Grapes

Variant	n	Total phenolic (TP) mg/g	Total flavonoid (TF) mg/g	Vitamin C (mg/100g)	Total carbohydrate (g/L)	Total acids (g/L)
		$\bar{x} \pm SD$	$\bar{x} \pm SD$	$\bar{x} \pm SD$	$\bar{x} \pm SD$	$\bar{x} \pm SD$
1	10	120.52 ± 0.25^{a}	45.23 ± 0.20^{a}	26.35 ± 0.23^{a}	172.25 ± 0.09^{a}	3.90 ± 0.21^{a}
2	10	128.39 ± 0.05^{b}	46.86 ± 0.31^{b}	28.15 ± 0.21^{b}	183.36 ± 0.03^{b}	4.50 ± 0.09^{b}
3	10	125.07 ± 0.09^{c}	46.01 ± 0.14^{c}	27.00 ± 0.02^{c}	175.17 ± 0.01^{c}	4.00 ± 0.06^{c}
4	10	131.75 ± 0.02^{d}	47.54 ± 0.06^{d}	26.90 ± 0.10^{a}	173.08 ± 0.13^{d}	4.25 ± 0.11^{d}
5	10	127.01 ± 0.19^{e}	46.57 ± 0.02^{e}	27.88 ± 0.07^{d}	177.69 ± 0.04^{e}	4.15 ± 0.18^{d}

$^{a, b, c}$ – values for the same parameter of the different variant marked with different letters have statistically significant difference ($p<0.05$), ANOVA, *post hoc* Tukey's test.

Table 4 shows the biochemical composition of grape samples across five treatment variants, with all parameters displaying statistically significant differences ($p < 0.05$). Variant 4 had the highest total phenolic content (131.75 ± 0.02 mg/g) and total flavonoid content (47.54 ± 0.06 mg/g), followed closely by Variant 2, which showed the highest vitamin C concentration (28.15 ± 0.21 mg/100g), total carbohydrates (183.36 ± 0.03 g/L), and total acids (4.50 ± 0.09 g/L). These values indicate a substantial improvement in grape biochemical quality compared to the control (Variant 1).

Variant 2 demonstrated the best results for vitamin C, carbohydrates, and acids, suggesting the foliar treatment at this concentration effectively enhanced the nutritional profile of the grapes. Variant 4, while showing slightly lower vitamin C and carbohydrate values, excelled in phenolic and flavonoid content, highlighting the positive impact of foliar fertilization on antioxidant components.

Variants 3 and 5 showed intermediate improvements in all measured parameters compared to the control but were generally lower than Variants 2 and 4.

The different superscript letters next to the means confirm significant differences among treatments, supporting the conclusion that foliar fertilization positively influences the chemical composition of 'Cardinal' grapes, enhancing their quality and potential health benefits.

Foliar treatments showed a positive effect on the chemical composition of grapes. In all examined parameters, a higher content was determined compared to the control variant. According to the research of Koureh et al. (2018), with the application of different doses of mineral and organic fertilizers in a commercial vineyard of white seedless grape, the content

of total phenolics ranged from 1.25 to 1.75 mg GAE g−1 FW, the content of total flavonoids from 0.568 to 0.697 mg CE g−1 FW, and antioxidant activity ranged from 61 to 75% DPPH.

Similarly, Shi et al. (2020) reported that with the application of different doses of mineral fertilizers in 10-year-old Marselan vines, the total phenolic content (mg/g) ranged from 2.52 to 3.42. Popovic et al. (2020) determined an average carbohydrate content of 14.57% and an average total acid content of 4.14% with the application of mineral and organic fertilizers in mixed grapevine 'Cardinal'.

Furthermore, according to Vijayalakshmi et al. (2022), fruit quality parameters were superior in berries from treatment T4 (100% RDF + 300 g Azotobacter + 300 g PSB + 300 g KRB/vine). Treatment T4 recorded the maximum total soluble solids (TSS) of 18.33 °Brix, minimum acidity (0.21%), highest TSS:Acid ratio (87.28), total sugars content (15.33%), reducing sugars (14.06%), and the highest sugar:acid ratio (73.00).

CONCLUSION

Based on the analyses conducted to determine the influence of soil and foliar fertilization on the chemical composition of the leaves, clusters, and grapes of the 'Cardinal' grapevine variety grown under the conditions of the Skopje vineyard area, it can be concluded that different concentrations of foliar fertilization play a significant role in the vegetative development of the grapevine. All investigated parameters showed significantly higher values ($p<0.05$) in the leaves, clusters, and grapes where foliar fertilization was applied, compared to the control variant.

Soil analysis continues to be of paramount importance, as integrating all available data helps in making informed decisions regarding fertilizer application rates. This ensures the adequate nutritional status of the grapevines without compromising the quality of the wine or the environment. Therefore, the rational use of fertilizers and nutrient-specific fertilization plans are highly recommended for vineyard management.

The combined application of soil and foliar fertilization, using mineral and organic fertilizers in optimal quantities, represents a fundamental prerequisite for the proper development of the grapevine and for improving the overall quality of grape production.

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INFLUENCE OF COVID-19 PANDEMIC ON ANTIBIOTIC RESISTANCE PROFILES OF PROTEUS MIRABILIS IN URINARY TRACT INFECTIONS: A RETROSPECTIVE ANALYSIS

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ABSTRACT

Introduction: COVID-19 pandemic brought unprecedented changes to healthcare systems worldwide, affecting not only the management of the pandemic disease but also the guidelines for the treatments of common infections. Due to the fact that urinary tract infections (UTIs) are among the most common infection's diseases, our focus is to investigate the prevalence of antibiotic resistance during the pandemic and to assess how pandemic-related treatments shifts may have influenced these resistance patterns. Among the pathogens responsible for UTIs, Proteus mirabilis has gained attention due to its increasing resistance to antibiotics. This study aims to evaluate the resistance patterns of Proteus mirabilis during 2020, a year which has been characterized by altered over prescription of antibiotics. *Methods*: A retrospective analysis was conducted from May to December 2020 on 78 urine cultures collected from ambulatory patients with UTIs signs. The data have been collected from the same microbiology laboratory with the main condition, that the methodology used was the same. Our focus was on the resistance rates of Proteus mirabilis to critically important antibiotics, particularly cephalosporins, nitrofurantoin, aminoglycoside and imipenem. *Results*: Our findings revealed high resistance rates of Proteus mirabilis to several cephalosporins, including cefepime, cefuroxime, ceftazidime and ceftriaxone, alongside significant resistance to nitrofurantoin and imipenem. This trend raises concerns about the effectiveness of standard empirical treatments for UTIs, especially in pandemic. *Conclusion*: The elevated antibiotic resistance observed in Proteus mirabilis during the COVID-19 pandemic may be linked to increased antibiotic usage practices influenced by the urgent need to manage various infections in a constrained healthcare environment. While it is essential to recognize that these instances remain relatively few. Continued surveillance is crucial to mitigate the risk of further resistance development.

Keywords: antibiotic resistance, Proteus mirabilis, ceftazidime, COVID-19, sensitivity

Introduction

COVID-19 pandemic represents a significant global health crisis. It has not only posed significant challenges to global health but has also influenced various aspects of medical practice, including the emergence of antibiotic resistance. As healthcare systems became overwhelmed with COVID-19 cases, changes in antibiotic prescribing patterns and increased use of broad-spectrum antibiotics may have contributed to a rise in antibiotic resistance. One notable concern is the impact on urinary tract infections (UTIs) caused by Proteus mirabilis, a common uropathogen known for its capacity to develop resistance to multiple antibiotics.

Urinary tract infections (UTIs) are prevalent clinical conditions primarily affecting the female population. Among the various uropathogens, Proteus mirabilis is recognized as a significant contributor to UTIs. Its virulence factors, including urease production and motility, facilitate its colonization in the urinary tract and contribute to its pathogenicity.

Understanding the antibiotic resistance profiles of Proteus mirabilis is crucial, as this directly influences clinical management and treatment outcomes for affected patients.

P. mirabilis, the third most prevalent cause of urinary tract infections (UTIs) and the second most common cause of catheter-associated urinary tract infections (CAUTIs) in long-term catheterized patients, is responsible for 12% of complicated UTIs.

This study aims to evaluate the resistance patterns of Proteus mirabilis during 2020, a year which has been characterized by altered over prescription of antibiotics.

Methods

- *Study design*

This retrospective study analyzed 78 patients with confirmed Proteus mirabilis positivity, collected from ambulatory patients with UTIs signs, conducted from May to December 2020, in Tirana, Albania. The data have been collected from the same microbiology laboratory with the main condition, that the methodology used was the same. The following methodologies were employed:

- *Patient selection and data collection*

A total of 78 patients with confirmed urinary tract infections caused by Proteus mirabilis were included in the study. Patients were selected from microbiology laboratory in Tirana district during the pandemic period May to December 2020.

Our focus was on the resistance rates of Proteus mirabilis to critically important antibiotics, particularly cephalosporins, nitrofurantoin, aminoglycoside and imipenem.

- *Urine sample collections*

Sample collection had been performed according to the protocol.

Clean catch midstream urine samples were collected to minimize contamination. Samples were transported to the laboratory within 2 hours and stored at 4ºC if there was a delay in processing.

- *Identification of pathogen*

Each urine sample was subjected to culture on Agar blood plate or CLED (Cysteine-lactose-electrolyte-deficient) agar to isolate uropathogens. Plates were incubated at 37°C for 24 hours.

Suspected colonies of P. mirabilis were identified based on colony morphology, gram staining and biochemical tests (urease, catalase and oxidase test).

Proteus swarms across the blood agar plate and gives no individual colonies.

Typically, the majority of *P. mirabilis* strains demonstrate a lack of lactose fermentation and a distinctive swarming motility. Gas and acid are formed during fermentation of glucose. Strong smell is also characteristic of Proteus.

These distinctive characteristics are readily discernable on agar plates, facilitating the efficient identification of *P. mirabilis*

Proteus mirabilis identification

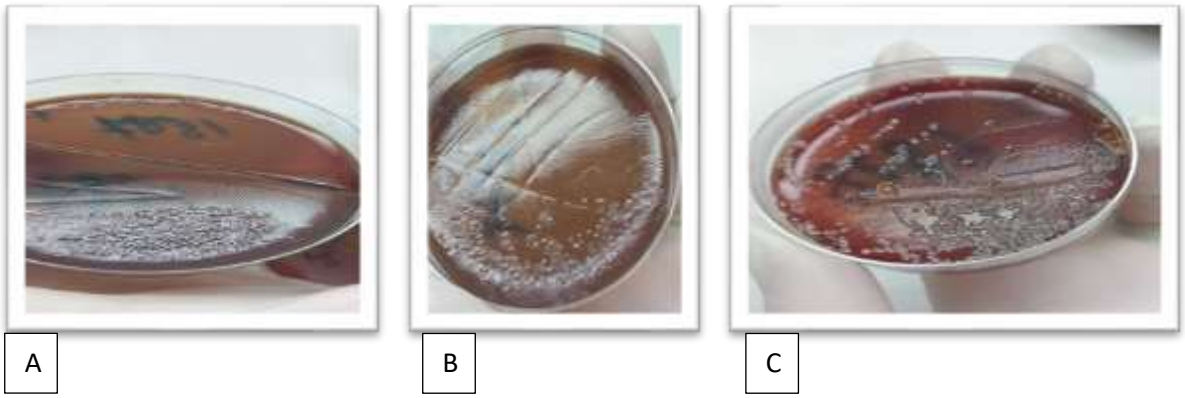

Fig.1 A) B) C) Proteus mirabilis, on a blood agar plate incubated 24h at 37°C.

The colonies are spreading on the surface of the agar due to P. mirabilis are swarming

- *Antibiotic susceptibility testing*

Antibiotic susceptibility testing was conducted on Mueller-Hinton agar, following the Clinical and Laboratory Standards Institute (CLSI) guidelines. This allowed for the evaluation of the sensitivity of isolated Proteus mirabilis strains to various antibiotics, providing crucial insights into resistance patterns. A standardized inoculum was prepared from identified colonies and adjusted to 0.5 McFarland standard. Antibiotic discs were placed on the surface of the agar, which was then incubated for 16-18 hours at 37ºC.

The following antibiotics were tested for antimicrobial sensitivity (AST): doxycycline (DOX), cefepime (FEP), cefuroxime (CXM), ciprofloxacin (CIP), piperacillin (PIP), tobramycin (TOB), ceftazidime (CAZ), gentamicin (Gen), ceftriaxone (CRO), nitrofurantoin (NIT), vancomycin (VAN), amoxicillin-clavulanate (AUG), imipenem (IMI), nalidixic acid (NAL). The isolate were assessed for sensitivity or resistance to these anti-microbial agents based on inhibitory zones.

Results

Each patient with Proteus mirabilis positivity had been tested for antibiotic resistance and sensitivity. During our 8 months of analysis different antibiotics had been checked and measured. The resistance patterns demonstrated high levels of resistance to multiple commonly used antibiotics. The highest resistance rates were observed with nitrofurantoin (57 cases resistant), ceftazidime (57) and cefuroxime (52). Moderate to high resistance was also noted with imipenem, ceftriaxone, gentamicin, vancomycin and piperacillin. ciprofloxacin exhibited a comparatively lower resistance rate with a higher number of sensitive isolates. Overall, the findings indicate a predominance of antimicrobial resistance among Proteus isolates, particularly toward beta-lactams, aminoglycosides and nitrofurantoin, while fluoroquinolones-especially ciprofloxacin and nalidixic acid, retained better activity against the isolates.

A notable observation is the very high resistance to beta-lactam antibiotics, including ceftazidime, cefuroxime, cefepime and ceftriaxone. This suggests widespread beta-lactamase production among the isolates, which is consistent with known resistance mechanisms in Proteus mirabilis. The elevated resistance to imipenem is particularly concerning, as carbapenems are typically reserved for more severe infections. Such resistance may indicate emerging carbapenem activity or other mechanisms of reduced carbapenem susceptibility, which warrant further investigation. Aminoglycoside resistance was also significant, with high resistance rates observed for tobramycin and gentamicin. Nitrofurantoin showed very poor activity, with the majority of isolates being resistant. This is expected, as Proteus species are intrinsically resistant to nitrofurantoin due to poor drug uptake and inactivation should not be used for Proteus urinary tract infections. In contrast, fluoroquinolones especially ciprofloxacin and nalidixic acid demonstrated better efficacy, with a higher proportion of sensitive isolates. This suggests that fluoroquinolones may remain among the more reliable empirical treatments options for UTIs caused by Proteus mirabilis, although resistance was still present and must be monitored. The overall resistance profile observed in this study reflects the global trend of increasing antimicrobial resistance among Gram-negative uropathogens.

Antibiotics	Resistant	Intermediate	Sensitive
DOXYCYCLINE	29	3	8
CEFEPIME	50	6	19
CEFUROXIME	52	6	18
CYPROFLOXACIN	22	6	48
PIPERACILLIN	24	15	37
TOBRAMYCIN	42	13	17
CEFTAZIDIME	57	7	11
GENTAMICIN	41	19	15
CEFTRIAXONE	42	12	22
NITROFURANTOINE	57	8	10
VANKOMYCIN	35	1	0
AUGMENTIN	24	3	9
IMIPENEM	47	8	20
NALIDIXIC ACID	10	15	46

Tab.1 Antibiotic susceptibility patterns of Proteus mirabilis

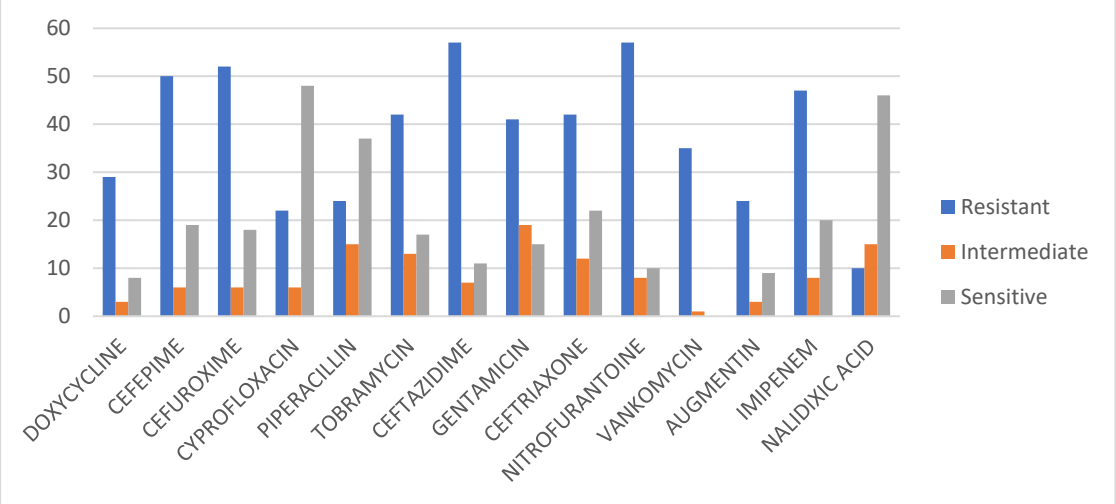

Fig.2 Proteus mirabilis antibiotic resistance and sensitivity

Discussion

Our study assessed the antimicrobial susceptibility patterns of Proteus mirabilis species isolated from urine cultures and revealed a high burden of antimicrobial resistance across multiple antibiotic classes. The findings underscore the increasing difficulty of managing urinary tract infections (UTIs) caused by P. mirabilis, a pathogen known for its intrinsic resistance mechanisms and ability to acquire additional resistance determinants. A prominent observation was the consistently high resistance to ß-lactam antibiotics, including cefuroxime, cefepime, ceftazidime and ceftriaxone. These results are suggestive of widespread expression of extended-spectrum ß-lactamases (ESBLs). Such resistance limits the effectiveness of first and second line ß-lactams. Aminoglycosides such as tobramycin and gentamicin also demonstrated considerable resistance. Those data diminished their utility in severe or complicated UTIs where aminoglycosides may serve as potent bacterial agents. The poor performance of nitrofurantoin seen in this study is consistent with the well-established intrinsic resistance of Proteus spp. to this agent, reaffirming that nitrofurantoin is inappropriate caused by this organism. Fluoroquinolones, especially ciprofloxacin and nalidixic acid showed comparatively better activity, with a higher proportion of isolates remaining sensitive. Over all the antimicrobial resistance patterns observed in this study reflect the global escalation of multi drug resistance among Gram-negative pathogens.

Conclusion

This study demonstrates that Proteus species isolates from urine cultures exhibit high levels of resistance to multiple classes of antibiotics, particularly ß-lactams, aminoglycosides and nitrofurantoin. The emergence of resistance to imipenem is especially troubling, as it reduces the effectiveness of drugs traditionally reserved for multidrug-resistant infections. Although fluoroquinolones showed relatively resistance was still present and warrants ongoing monitoring. The overall findings emphasize the urgent need for continuous antimicrobial resistance surveillance and evidence-based empirical treatment guidelines. Further research, including molecular studies is recommended to characterize the underlying mechanisms of resistance.

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TİCARİ LASTİKLERDE STATİK BALANS ANALİZİ

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ÖZET

Lastikler, otomotiv sektörünün temel güvenlik bileşenlerinden biri olarak araçların yol tutuşu, frenleme performansı ve genel sürüş güvenliği açısından kritik bir öneme sahiptir. Lastik yapısında yer alan ana bileşenler arasında kauçuk karışımları, çelik ve naylon gibi tekstil takviyeleri ile yanak bölgeleri bulunmaktadır. Her bir bileşenin fiziksel ve kimyasal özellikleri, lastiğin dayanıklılığını, esnekliğini, yuvarlanma direncini ve yol ile temas yüzeyini doğrudan etkilemektedir. Bu bileşenlerin üretim sürecindeki yerleştirme pozisyonu kadar, birbirine birleştirildiği ek yerleri de yapısal bütünlük açısından büyük önem taşımaktadır. Özellikle ham lastik üretiminde, bileşenlerin birleştirildiği ek yerlerinin birbirine göre açısal konumu, lastiğin statik balans çıktısı üzerinde belirgin etkiler göstermektedir. Statik balans, lastiğin dengeli dönüş kabiliyetiyle doğrudan ilişkilidir ve sürüş konforunu önemli ölçüde etkiler. Bu çalışmada lastik performansını iyileştirmek için fabrika ortamında gerçekleştirilen proses iyileştirme çalışmaları sonucunda ek yerlerinin yerleşimi optimize edilmiş ve statik balans değerlerinde kayda değer iyileştirmeler sağlanmıştır. Bu iyileştirmelerle üretim hattındaki operasyonel ıskartaların azaltmanın yanı sıra, aynı zamanda bayilerde yapılan balanslama işlemlerinde kullanılan kurşun ağırlık miktarını da önemli ölçüde düşürmüştür. Çalışma sonucunda hem maliyet avantajı hem de çevresel sürdürülebilirlik açısından iyileştirmeler elde edilmiştir.

Anahtar Kelimeler: Lastik, Statik Balans, Lastik İmal Makinası, Lastik Sınıflandırma Makinası, Kurşun Azaltma, Proses İyileştirme, Görüntü işleme.

ANALYSIS OF STATIC BALANCE STATUS IN COMMERCIAL TIRES

ABSTRACT

Tires, as one of the fundamental safety components of the automotive industry, play a critical role in vehicle handling, braking performance, and overall driving safety. The main components of a tire include rubber compounds, textile reinforcements such as steel and nylon, and sidewall sections. The physical and chemical properties of each component directly affect the tire's durability, flexibility, rolling resistance, and contact surface with the road. In addition to the positioning of these components during the manufacturing process, the splice locations where they are joined together are also of great importance for maintaining structural integrity. In particular, in raw tire production, the angular alignment of the splice joints relative to each other has a significant effect on the tire's static balance performance. Static balance is directly related to the tire's ability to rotate smoothly and has a major impact on driving comfort. In this study, process improvement efforts carried out under factory conditions were implemented to optimize the positioning of the splice joints, resulting in notable improvements in static balance values. These improvements not only reduced operational scrap rates on the production line but also significantly decreased the amount of lead weights used during balancing operations at dealerships. As a result of the study, enhancements were achieved in both cost efficiency and environmental sustainability.

Keywords: Tire, Static Balance, Tire Building Machine, Tire Classification Machine, Lead Reduction, Process Improvement, Image Processing

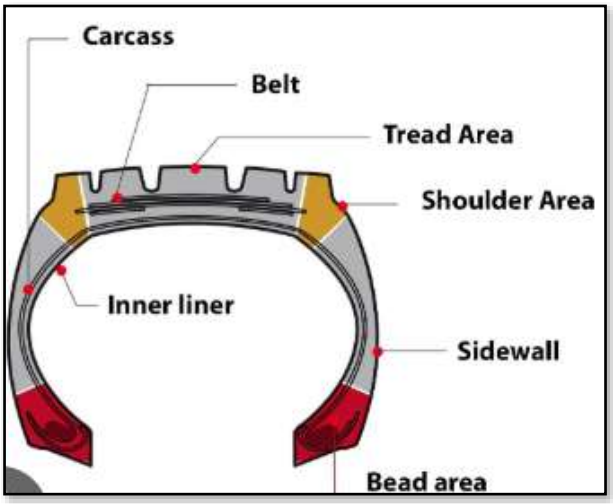
GİRİŞ

Lastikler, araçların güvenli hareketini sağlayan en önemli bileşenlerden biridir [1]. Özellikle ticari araçlarda, lastiklerin balansı hem sürüş konforu hem de güvenlik açısından kritik öneme sahiptir. Statik balans, lastiğin herhangi bir noktada ağırlık dengesizliği göstermemesi anlamına gelir. Bu dengesizlikler, üretim sürecindeki bileşen dağılımı, birleşim hataları veya malzeme kusurlarından kaynaklanabilir. Statik balansın sağlanamaması, araçta titreşimlere, düzensiz lastik aşınmasına ve sürüş güvenliğinin azalmasına yol açabilir [2]. Bu dengesizlikler, üretim sürecindeki bileşen dağılımı, birleşim hataları veya malzeme kusurlarından kaynaklanabilir [3]. Literatürde belirtildiği üzere, lastik uniformitesindeki (düzenliliğindeki) bozulmalar; radyal ve yanal kuvvet değişimlerine neden olarak araç dinamiğini olumsuz etkiler [4]. Statik balansın sağlanamaması, araçta istenmeyen titreşimlere, düzensiz lastik aşınmasına ve sürüş güvenliğinin azalmasına yol açabilir [5]. Ticari araçlarda bu tür problemler, hem sürücü hem de yolcular için risk oluşturur; ayrıca işletmelerin bakım maliyetlerini artırabilir. Modern lastik üretiminde, statik balansın sağlanmasına yönelik olarak gelişmiş kalite kontrol süreçleri ve test yöntemleri uygulanmaktadır. Üretim hattında bileşenlerin doğru dağılımı ve birleşim noktalarının hassas kontrolü için endüstriyel otomasyon ve görüntü işleme teknolojileri kullanılmakta, böylece olası dengesizlikler erken aşamada tespit edilip giderilmektedir [6]. Bu çalışmada, Brisa fabrikasında üretilen ticari lastiklerde statik balansın sağlanmasına yönelik süreçler ve yapılan iyileştirmeler detaylı olarak ele alınmıştır.

MATERYAL VE YÖNTEM

Lastik ve Bileşenleri

Bir lastik, otomotiv sektöründe güvenli ve verimli sürüşün temelini oluşturan, çok katmanlı ve karmaşık bir mühendislik ürünüdür [7]. Temel olarak çelik teller, doğal ve sentetik kauçuk, tekstil takviyeleri ve çeşitli kimyasal katkı maddelerinin hassas bir şekilde bir araya getirilmesiyle üretilir. Ticari lastiklerde karkas, sırt, yanak ve iç astar gibi ana bileşenler bulunur [3]. Şekil 1'de kesit analizi alınmış lastiğin görseli gösterilmektedir. Her bir bileşenin üretim sürecindeki miktarı, yerleşimi ve dağılımı, lastiğin genel performansını ve özellikle balansını doğrudan etkiler. Özellikle birleşim noktalarında (splice) oluşan dengesizlikler, statik balans sorunlarının en önemli nedenlerinden biridir ve bu nedenle üretim sırasında büyük bir hassasiyet gerektirir.



Şekil 1 : Lastiğin kesit görseli

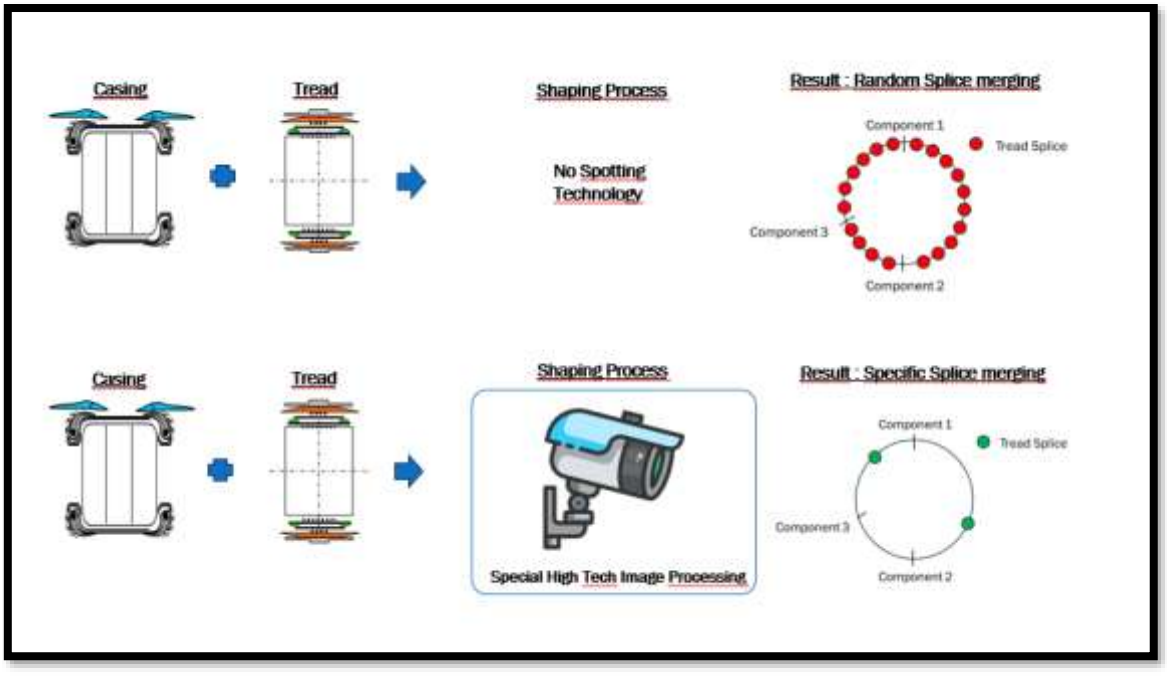
Statik Balansın Tanımı ve Önemi

Statik balans, bir lastiğin sabit bir eksende döndürüldüğünde herhangi bir noktada ağırlık fazlalığı veya eksikliği göstermemesi durumudur. Lastikteki ağırlık dengesizliği, aracın hareketi sırasında titreşimlere, düzensiz lastik aşınmasına ve sürüş güvenliğinin azalmasına neden olabilir. Özellikle ticari araçlarda, statik balansın sağlanamaması hem sürücü hem de yolcular için ciddi riskler oluşturur ve işletmelerin bakım maliyetlerini artırır. Statik balansın önemi, lastiğin üretim sürecinde bileşenlerin doğru yerleştirilmesi ve birleşim noktalarının hassas kontrolüyle doğrudan ilişkilidir. Bu nedenle, modern üretim tesislerinde gelişmiş test yöntemleri ve kalite kontrol süreçleriyle statik balans sürekli olarak izlenir ve iyileştirilir.

Brisa'da Uygulanan Geliştirme Faliyeti

Brisa fabrikasında, lastiklerin statik balansı çeşitli testlerle kontrol edilmektedir. Dinamik testler (yuvarlanma direnci, karkas dayanıklılığı, bead burst analizi), gürültü testleri ve titreşim önleme ölçümleri bu süreçte önemli rol oynar. Ayrıca, üretim hattında bileşenlerin doğru dağılımı ve birleşim noktalarının hassas kontrolü için, endüstri 4.0 uygulamaları kapsamında ileri görüntü işleme teknolojileri kullanılmaktadır [8].

Fakat her fabrikada teknolojik cihazlar ve ekipmanlar zamana bağlı olarak eskimektedir. Bu eskimelerin yenileriyle değiştirilme süreci maliyet açısından çok maliyetli olduğu için bazen uygulanabilir en hızlı ve basit yöntemler tercih edilmektedir. Bu süreç uygulanacak proses için bazen kolay olsa da bazen de çok zor ve uygulabilir olmamaktadır. Brisa da yapılan görüntü işleme teknoloji yardımıyla büyük bütçeli uygulanacak uygulama yerine daha basit ve görece hızlı uygulabilir system kurulumu gerçekleştirilmiştir.



Şekil 2 : Geliştirme Yapılan Çalışma

BULGULAR

Brisa fabrikasında yürütülen bu kapsamlı çalışmada, lastik imalat sürecine entegre edilen görüntü işleme tabanlı kontrol sistemleri ile statik balans performansında önemli kazanımlar elde edilmiştir. Geleneksel üretim yöntemlerinde, lastiği oluşturan yarı mamul bileşenlerin ek yerleri, operatör inisiyatifine veya makine hızına bağlı olarak rastgele bir dağılım

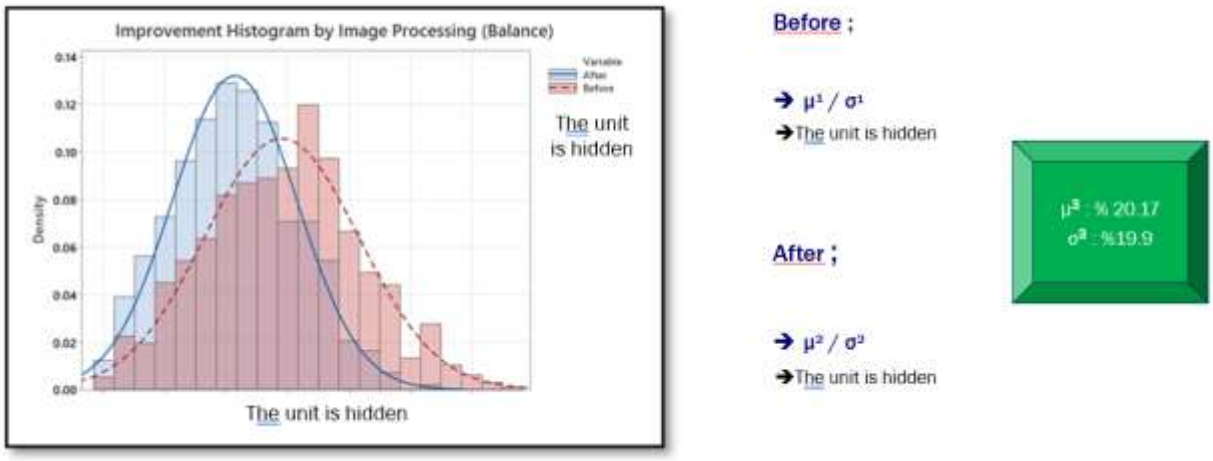
göstermekteydi. Literatürde "Random Splice Merging" olarak adlandırılan bu durum, bileşenlerin ağırlık merkezlerinin üst üste binmesine ve toplam dengesizliğin artmasına neden olmaktadır.

Yapılan iyileştirme ile lastik imalat makinasına yerleştirilen kameralar ve geliştirilen algoritma sayesinde, her bir bileşenin ek yeri anlık olarak tespit edilmiştir. Bu veriler kullanılarak, bileşenlerin ek yerlerinin birbirini dengeleyecek şekilde (örneğin 180 derece zıt veya belirli açılarla dağıtılmış) konumlandırılması sağlanmıştır. Bu yöntem, vektörel olarak dengesizlik kuvvetlerinin sönümlenmesi prensibine dayanmaktadır [9].

Elde edilen veriler istatistiksel olarak analiz edildiğinde, Şekil 3'te sunulan "Öncesi-Sonrası" histogram grafiklerinde açıkça görüldüğü üzere, proses dağılımında belirgin bir daralma meydana gelmiştir. İyileştirme çalışmaları sonucunda:

- ***Ortalama Değer (μ):*** Balans dağılım eğrisinin merkezi, sıfır noktasına (ideal dengeye) daha fazla yaklaşmış,
- ***Standart Sapma (σ):*** Verilerin yayılımı azalarak proses kararlılığı artırılmıştır.

Sayısal olarak, statik balansın hem ortalama hem de standart sapma değerlerinde %20'ye yakın bir iyileşme sağlanmıştır. Standart sapmadaki bu düşüş, üretilen lastiklerin kalitesinin daha tutarlı hale geldiğini ve üretim hattındaki varyasyonların minimize edildiğini göstermektedir. Bu gelişmeler, nihai ürün kalitesini doğrudan artırırken, üretim hattındaki plansız duruşları ve yeniden işlem (re-work) oranlarını düşürerek toplam üretim verimliliğine katkı sağlamıştır.



Şekil 3 : Çalışma öncesi ve sonrası histogramı

SONUÇ

Ticari araç güvenliği ve sürüş konforu açısından kritik bir parametre olan statik balansın, üretim aşamasında kontrol altına alınması modern lastik mühendisliğinin öncelikli hedeflerinden biridir. Bu çalışmada, Brisa üretim tesislerinde uygulanan görüntü işleme destekli proses optimizasyonunun, lastik uniformitesi üzerindeki pozitif etkileri deneysel verilerle kanıtlanmıştır.

Elde edilen sonuçlar iki ana başlıkta değerlendirilebilir:

1. ***Üretim Verimliliği ve Maliyet:*** Fabrika sahasında statik balans limitleri dışında kalan (ıskarta veya tamir gerektiren) lastik miktarında azalma sağlanarak, atık maliyetleri düşürülmüş ve hammadde verimliliği artırılmıştır.

2. ***Müşteri Memnuniyeti ve Çevresel Etki:*** Lastiklerin fabrika çıkışında daha dengeli olması, son kullanıcıya ulaştığında bayilerde yapılan balans ayarı işlemlerini kolaylaştırmıştır. Araç üzerine takılan kurşun ağırlık (balans kurşunu) miktarının azalması, hem servis süresini kısaltmış hem de çevreye zararlı bir ağır metal olan kurşun kullanımını minimize ederek çevresel sürdürülebilirlik hedeflerine katkı sunmuştur.

Sonuç olarak, yüksek maliyetli ekipman yatırımları yerine, mevcut üretim hattına entegre edilen akıllı algılama sistemleri ve proses mühendisliği yaklaşımları ile kalite parametrelerinde sürdürülebilir iyileştirmeler sağlanabileceği gösterilmiştir.

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DEEP LEARNING-BASED DETECTION AND TRACKING OF SUNN PEST DAMAGE ON WHEAT GRAINS USING YOLO AND MOT

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ABSTRACT

This study presents a deep learning–based approach for the automatic detection of feeding damage (emgi) caused by the sunn pest (*Eurygaster integriceps*) on wheat grains. A custom dataset containing healthy, damaged, and foreign-material grain instances was constructed and annotated in YOLO format, and three modern YOLO families—YOLOv8, YOLOv11, and YOLOv12—were systematically evaluated across their S/M/L variants under identical hyperparameters to ensure fair comparison. Experimental results demonstrate that YOLOv12 and YOLOv11 architectures exhibit superior capability in distinguishing fine-grained morphological differences, with YOLOv12l achieving the highest performance (mAP50=0.944) and near-perfect detection in the damaged class. YOLOv8, while competitive overall, showed limitations particularly in recall for damaged grains, indicating sensitivity to subtle surface deformations. The results further reveal that the YOLOv12 family offers an optimal balance between model size and accuracy, with even the lightweight YOLOv12s achieving high mAP values. To assess real-time applicability, the best-performing model was integrated with a ByteTrack-based multi-object tracking module, which successfully maintained consistent IDs and stable tracking across video frames, proving the system's suitability for dynamic environments such as industrial quality-control lines. Overall, the findings highlight the strong potential of modern YOLO architectures in detecting microscopic pest-induced damage and demonstrate that the developed system can serve as a fast, reliable, and scalable alternative to manual inspection in agricultural quality assessment.

1. Introduction

The sunn pest (Eurygaster integriceps) is known as one of the pests that most significantly affect yield and quality in wheat production in Türkiye [1]. Especially during the milk stage, the sunn pest feeds by extracting sap from wheat grains, and through various enzymes it secretes, it causes deterioration in the gluten structure of the grain, a decrease in germination capacity, and a severe weakening of flour quality [2]. This enzymatic effect directly reduces the processability of bread and pasta products, leading to quality losses in the domestic market as well as economic declines in export potential. Therefore, in countries such as Türkiye, where wheat is a strategic agricultural product, the accurate, rapid, and standardized detection of sunn pest feeding damage is of vital importance for producers, inspection institutions, and industrial organizations [3].

Today, the determination of feeding damage is mostly based on manual inspections carried out by experts, and these methods carry significant limitations as they are both time-consuming and open to subjective interpretation [4]. In large-volume sampling, the prolongation of the evaluation process, the increase in human-induced error rates, and the difficulty of standardization reduce the effectiveness of manual methods. In addition, the fact that the damage is small-sized and sometimes difficult to distinguish visually makes visual inspection processes even more complex. In recent years, artificial intelligence and deep learning-based computer vision methods have emerged as a strong alternative in agricultural quality control processes. Deep learning models provide high accuracy and speed especially in tasks such as object detection and the classification of fine textural differences, making it possible to detect even micro-level damage that is difficult for the human eye to perceive. This enables quality-defining factors such as feeding damage to be analyzed automatically and reliably, creating significant advantages in terms of both time and cost [5–7].

The primary aim of this study is to automatically detect feeding damage caused by the sunn pest on wheat grains using deep learning-based methods. In this context, different object detection models belonging to the YOLO family were evaluated, and an artificial intelligence approach was developed to determine feeding damage from images with high accuracy.

Motie and colleagues developed a classification model using drone-acquired RGB and near-infrared (NIR) images to detect wheat spike damage caused by the sunn pest at an early stage. In the study, various vegetation indices (such as NDVI, RVI, DVI, RED and GREEN band reflectance) were calculated, and these features were evaluated with SVM (Radial Basis Function kernel) classifiers. It was shown that, in NIR images, the reflectance of red and near-infrared bands and the RVI index, and in visible-light images, the reflectance of red and green bands and the NGBDI index, contributed most to classification performance. SVM models achieved the highest accuracy in February and March when wheat plants were still green; average accuracy was reported as 97% for NIR images and 93% for visible-light images. These findings demonstrate that drone-based imaging and machine learning methods provide an effective approach for detecting spike damage caused by the sunn pest [8].

Moon's study proposes a deep learning and image processing-based framework for detecting wheat leaf diseases. In the study, color-based segmentation and GLCM methods were applied to extract features from leaf images; the obtained features were tested with classifiers such as Naïve Bayes, k-NN, SVM, and Random Forest. The results showed that among the models, Random Forest achieved the highest performance, reaching an accuracy of 98.9%. The study demonstrates that this approach offers high accuracy in the automatic diagnosis of wheat diseases and provides a faster and more reliable solution compared with traditional manual evaluations [9].

Akman and colleagues presented a wheat grain dataset with high species diversity to investigate kernel damage caused by the sunn pest across different wheat varieties, designed to reflect real production conditions. In the study, healthy and sunn pest–damaged grains from six different wheat species were collected using high-resolution imaging while considering realistic scenarios such as natural piling, touching grains, and the presence of broken and half kernels. The authors demonstrated in detail that the dataset is well suited for classification, detection, and segmentation tasks using machine learning and deep learning approaches. In this respect, the study distinguishes itself from existing datasets in the literature that are limited in scope and mostly created under synthetic conditions, providing a more realistic and generalizable reference resource for industrial sorting and quality control applications [10].

2. Materials and Methods

2.1. Dataset

The image data used in this study were generated on wheat samples brought to the laboratory from different geographical regions. The grains were freely distributed on a homogeneous surface and recorded with a high-resolution camera system, and each image was arranged to clearly display the feeding damage (emgi) left by the sunn pest on the wheat grain. Three main classes were used in the study: damaged grain, undamaged grain, and foreign material. All images were manually annotated by experts, and then converted into YOLO format to obtain a bounding-box-based structure. Due to the dataset containing a high density of small objects, data augmentation techniques such as rotation, brightness variation, scaling, and mirroring were utilized when necessary to enable the model to learn a more stable representation.

The constructed dataset was organized to provide a balanced class distribution and was carefully divided into training, validation, and test subsets. In total, 11,649 grain instances were annotated across 71 images. The training set, with 9,239 samples, constituted the largest portion of the dataset, while the validation set contained 773 samples and the test set included 1,637 samples. This structure enabled the models to learn robustly and allowed generalization performance to be measured accurately. The class counts and distribution of the dataset are presented in Table 1, forming an appropriate foundation for YOLO-based detection of sunn pest feeding damage.

Table 1. Class-Wise Data Distribution for Healthy, Damaged, and Foreign Materials Categories

Class	Veri Sayısı
Un-Healthy	1872
Damaged	5214
Foreign Materials	4563

2.2. YOLO-Based Object Detection Models

In this study, modern deep learning–based object detection methods were used to automatically identify the feeding damage caused by the sunn pest on wheat grains. The analysis process is based on a specially constructed image dataset, standardized preprocessing steps, and a comparative evaluation of models belonging to three different YOLO families. In the first stage, a two-class dataset containing damaged and healthy wheat grains was created, and all images were obtained under homogeneous lighting conditions using a high-resolution camera. The annotation process was carried out under expert guidance; the images were classified under

the labels “s” (healthy), “e” (damaged), and “y” (foreign material). All annotations were prepared in a bounding-box structure suitable for YOLO format, thus ensuring a consistent training flow across different models.

The YOLO (You Only Look Once) architecture adopts a one-stage object detection approach, performing both class prediction and localization in a single forward pass over the image. Its real-time performance, high speed–accuracy trade-off, and success in small-object detection make it widely preferred in agricultural image analysis. The fundamental principle of YOLO is dividing the image into grids and estimating object probability and bounding box parameters from each cell. The YOLOv8, YOLOv11, and YOLOv12 versions used in this study incorporate increasingly advanced backbones, optimized feature pyramid structures, context-aware attention mechanisms, and enhanced scales for improved small-object detection [11–14]. YOLOv8, with its efficiency and simplified structure, was evaluated as a reference model, while YOLOv11 was designed with a deeper and wider architecture, aiming to provide higher discriminative power particularly for small objects with complex morphological structures. YOLOv12, on the other hand, integrates next-generation modules such as “Partial Convolution Fusion,” “Dynamic Head,” and adaptive feature transfer across scales, further improving both localization accuracy and detection stability. For this reason, it is highly suitable for detecting small and localized damage regions such as sunn pest feeding damage. The basic representation of the YOLO architecture is given in Figure 1.

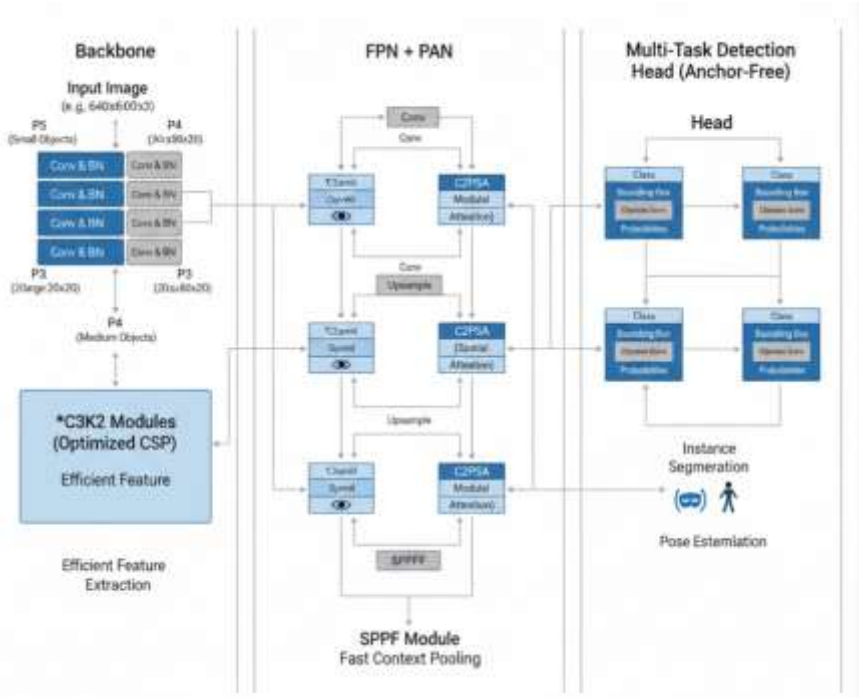

Figure 1. Yolo Architechure

Before being included in the training process, the data were subjected to basic preprocessing steps such as resizing, normalization, and brightness–contrast adjustment; and to increase the generalization ability of the model, data augmentation methods such as horizontal–vertical flipping, rotation, scaling, and brightness variations were applied. The dataset was divided into train–validation–test subsets, and the same data distribution was preserved across all models to ensure that the experiments were conducted fairly.

In the modeling process, three different YOLO families were used: YOLOv8, YOLOv11 (S/M/L), and YOLOv12 (S/M/L). While YOLOv8 was evaluated as a reference model due to

its lightweight and fast structure, the YOLOv11 and YOLOv12 versions were compared across different size variants to examine the relationship between model capacity and accuracy. These models, with their advanced feature extraction structures, different backbones, and improvements in object detection performance, provide significant advantages in identifying small, localized, and morphologically subtle structures such as feeding damage. The single-stage structure of all three versions, their ability to operate at high FPS rates, and the strengthened small-object detection capability provided by the FPN/PAN structure make it possible to accurately identify small damage regions in agricultural images.

All models were trained in the GPU-accelerated environment of Google Colab Pro+. Using the same hyperparameters across all models is a fundamental component of the study design. In this context, the number of epochs was fixed at 100, the batch size at 16, the input size at 640×640 pixels, the learning rate at 0.001, and the randomness value (seed=42) remained constant. Thus, differences arising from hyperparameters were eliminated in model comparisons. During the optimization phase, the models were trained with an AdamW-based structure in accordance with the default settings of the Ultralytics library; and the default CIoU-based components of YOLO models were used as the loss function. Automatic Mixed Precision (AMP) was enabled during training, providing efficiency in both speed and memory usage. At the end of each epoch, validation evaluation was performed, and the weight file with the best performance was saved. Early stopping was not used, and all models completed their full training cycles. The hyperparameters used during model training are summarized in Table 2.

Table 2. Training Hyperparameters Used in the YOLO Models

Hiperparameter	**Value**
Epoch	100
Image Size (imgsz)	640 px
Batch Size	16
Seed	42
Patience	0 *(early stopping not used)*
Data Split	Train / Valid / Test
YAML Config	3 class (s, e, y)

The performance of the models was evaluated using the mAP@50, precision, recall, and F1-score metrics commonly used in the object detection literature. Additionally, normalized and raw confusion matrices were generated to examine the models' discrimination power at the class level. During the evaluation phase, a fixed confidence value (conf=0.001) and IoU threshold (IoU=0.50) were used for all models. The results obtained were compared in terms of both classification accuracy and geometric accuracy of the detection boxes; performance in small object detection was the main analysis criterion, particularly because the grasshopper's small structural changes make it difficult to detect.

In another phase of the study, a ByteTrack-based multi-object tracking system was used to examine the behavior of detected objects in real-time scenarios. Test videos were processed frame by frame, assigning an ID to each grain, displaying detected classes with color codes, and examining tracking performance. This allowed evaluating whether the model demonstrated stability not only in static images but also in dynamic flows closer to the production line. As a

result of all these steps, YOLO models of different sizes and architectures were tested under the same training conditions to determine the most suitable model structure for detecting wheat weevils. The findings show that deep learning-based object detection models offer significant advantages over manual methods by providing high accuracy and speed in wheat quality control processes.

2.3. Multi Object Tracking

In this study, multi-object tracking (MOT) was applied after the object detection phase to evaluate the model's behavior in video-based processes [15]. For this purpose, the detection boxes produced by YOLO models were combined using the ByteTrack algorithm, and a unique ID was assigned to each wheat grain. The MOT process relies on associating detections across frames to ensure consistent tracking of the same object in consecutive frames. The flowchart for the Multi-Object Tracking process is shown in Figure 2.

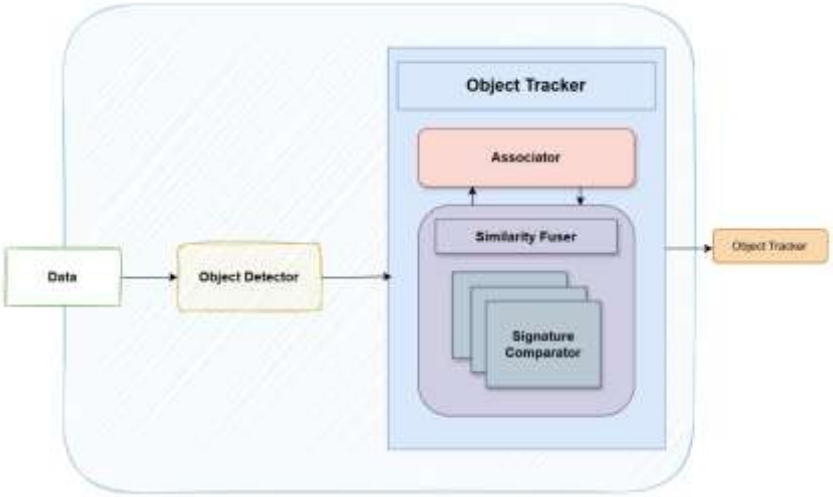

Figure 2. General MOT architecture that performs multi-object tracking by applying similarity computation and association steps after object detection.

In the method, test videos were first analyzed in terms of basic features such as frame rate (FPS), resolution, and total number of frames. Each frame was then sent to the YOLO model, which returned detection boxes containing class labels, location information, and confidence scores. These detections were passed to the ByteTrack tracker, which established relationships between objects based on criteria such as center position similarity, box overlap ratio, and confidence scores. This ensured that the same object was represented by the same ID across consecutive frames.

3. Experimental Result

In this study, YOLOv8, YOLOv11, and YOLOv12 models with different size variants (S/M/L) were evaluated to automatically detect the feeding damage caused by the sunn pest. Since the models were trained with the same hyperparameters, performance differences were ensured to originate solely from the architectural structure. The obtained results generally indicate that all models achieved high accuracy levels, but particularly the YOLOv12 and YOLOv11 architectures performed class discrimination more reliably.

The YOLOv12 family stood out as the best-performing group in the study. The YOLOv12l model presented the most balanced results with Precision=0.928, Recall=0.946, and mAP50=0.944 across all classes. In the “e” class (damaged grain), almost error-free detection

was achieved with 99.7% precision and 99.7% recall. Similarly, the YOLOv12m model also exhibited strong performance with mAP50=0.94. The lightweight variant YOLOv12s achieved high accuracy with mAP50=0.942 despite its small parameter size; this indicates that the architecture performs efficient feature extraction. The performance metric results of the YOLOv12 models are presented in Table 3.

Table 3. Performance comparison of YOLOv12 models based on mAP50, precision, and recall metrics.

Model/Metric	mAP50	Precision	Recall
YOLOv12s	0.942	0. 939	0.947
YOLOv12m	0.940	0.914	0.942
YOLOv12l	0.944	0.928	9.946

Among the YOLOv12 models, the YOLOv12l model achieved the highest accuracy. It surpassed all other models in terms of maAP50 and other metrics, both class-based and model generalization. Figure 3 shows the confusion matrix for the results obtained by the YOLOv12l architecture.

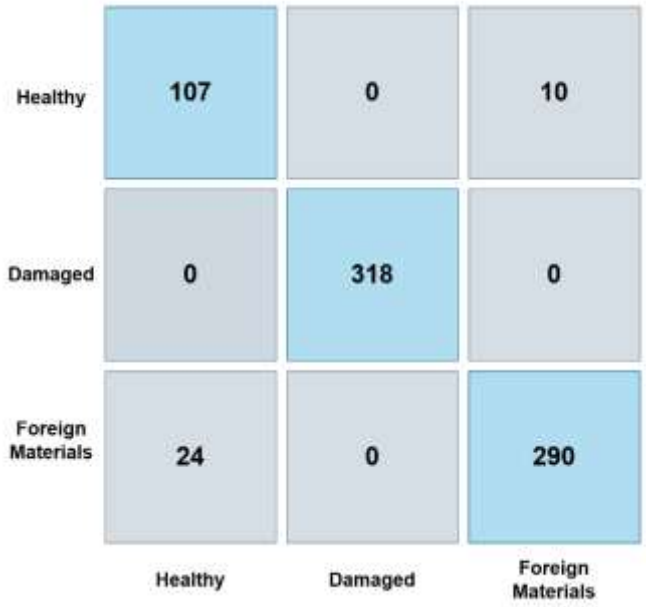

Figure 3. Confusion matrix presenting the overall prediction performance of the YOLOv12-L model.

The YOLOv11 models were the YOLO family that achieved the most successful results after the YOLOv12 models. In this group, the model that provided the highest accuracy rate was YOLOv11m. YOLOv11m reached extremely successful results, especially in detecting damaged grains, with Precision=0.993, Recall=0.997, and mAP50=0.992. The YOLOv11l model, on the other hand, constituted the second strongest model group of the study with mAP50=0.913 in overall performance. Although the YOLOv11s model is small in size, it

demonstrated a satisfactory performance with Precision=0.907. The performance metric results of the YOLOv11 models are presented in Table 4.

Table 4. Performance comparison of YOLOv11 models based on mAP50, precision, and recall metrics.

Model/Metric	mAP50	Precision	Recall
YOLOv11s	0.899	0.907	0.912
YOLOv11m	0.942	0.932	0.941
YOLOv11l	0.913	0.937	0.916

For comparison purposes, the YOLOv8 model lagged behind the other architectures in the study. The overall performance of YOLOv8 was realized as Precision=0.839, Recall=0.860, and mAP50=0.885. The low recall value particularly in the "damaged" class indicates that this architecture is more sensitive to class imbalances. On the other hand, achieving over 98% recall in the "healthy" class reveals that the model is successful in correctly identifying healthy grains. The performance evaluation metric results for YOLOv8 are presented in Table 5.

Table 5. Performance comparison of YOLOv8 model based on mAP50, precision, and recall metrics.

Model/Metric	mAP50	Precision	Recall
YOLOv8	0.885	0.839	0.860

When evaluated overall, it was observed that the YOLOv12 and YOLOv11 models demonstrated significantly superior performance compared to YOLOv8 in terms of both mAP values and class-based accuracy levels. In particular, YOLOv12l stood out as the most suitable model of the study with its balance between high accuracy and low computational cost. The results show that modern YOLO architectures can achieve high success in detecting small morphological changes such as sunn pest feeding damage and offer a fast, stable, and scalable solution compared to manual methods.

The model that achieved the highest accuracy during the training phase was integrated into the multi-object tracking (MOT) process in order to evaluate whether feeding damage could be tracked consistently under real-time conditions. In this context, the tracking system was created by combining YOLO's detection outputs with a ByteTrack-based tracker. The ByteTrack algorithm assigns a unique identity (ID) to each wheat grain by performing inter-frame association among high-confidence boxes while filtering out low-confidence boxes. Thus, the grains are tracked throughout the video, their physical movement is captured even if their class does not change, and the behavior of the grain over time can be recorded.

In the testing phase, the video uploaded by the user was first automatically analyzed in terms of frame count, resolution, and FPS values. Then, the YOLO model processed the video frame by frame, generating detection boxes, class labels, and tracking identities for each frame. With the color scheme defined in the code, the "healthy (s)," "damaged (e)," and "foreign material (y)" classes were visually distinguished; and both the class label and ID information were added to each detection box. An example frame from a tracking video is presented in Figure x. Thanks to this structure, even if the same grain appeared in different frames, it could be tracked

through the same ID, which provided the continuity information required in quality control production lines.

The newly generated frames were recombined into an MP4 output video and saved to evaluate the real-time performance of the model. An inference time of approximately 20–25 ms was obtained during the video processing phase, confirming that the model is suitable for real-time operation. The minimal occurrence of ID losses during tracking demonstrated that ByteTrack worked in harmony with YOLO and that the object association performance was high.

4. Discussion

In this study, the YOLO-based deep learning models used for the automatic detection of feeding damage caused by the sunn pest on wheat grains demonstrated a high level of accuracy in both static images and real-time video conditions. The experimental findings show that especially the YOLOv12 and YOLOv11 architectures possess strong discriminative capacity in classifying feeding damage. The nearly error-free detection of the “damaged” class by the YOLOv12m and YOLOv12l models reveals that the small morphological deteriorations on the wheat grain surface can be successfully captured by deep feature maps. In contrast, although YOLOv8 is competitive in overall accuracy, it lagged behind the most recent architectures in the study with a lower recall value particularly in the damaged class. This indicates that older YOLO architectures are limited in modeling complex surface deformations.

When the relationship between model size and accuracy is examined, it is seen that the YOLOv12 family offers a remarkable balance. Even the YOLOv12s model, which has a low number of parameters, achieved a high mAP50 value; this shows that the architecture provides strong representational capability even in lightweight variants. As the model size increased, an improvement in accuracy was observed, but the YOLOv12l model stood out as the most efficient option in terms of computational cost and performance. The YOLOv11 models also produced stable and high-accuracy results, particularly in the “healthy” and “foreign material” classes. These findings suggest that although architectural depth and parameter count have a significant effect, the most critical factor is the structural optimization of feature extraction and multi-scale detection layers used in the model.

The MOT and ID tracking results obtained under real-time scenarios demonstrated that the models also exhibited stable performance in dynamic environments. The tracking process performed with the ByteTrack algorithm showed that the grains could be followed across frames with high consistency, and ID losses occurred at a minimal level. This indicates that the developed system is applicable not only in laboratory settings but also in areas such as industrial quality control lines where continuous flow exists. Additionally, the uninterrupted preservation of class labels throughout the video enables the analysis of grain movement behavior in addition to feeding damage detection. Such a structure is expected to contribute to the early separation of damaged grains in the production line by being integrated with supply chain tracking systems. On the other hand, the study also has some limitations. The fact that the dataset was obtained under specific lighting conditions suggests that the model may require additional adaptations in different imaging environments. Similarly, feeding damage may appear with varying intensities on the surface, and the variability of class boundaries according to experts makes the annotation process difficult. However, the high performance of YOLOv12 models even under these challenging conditions demonstrates that the architecture is flexible against diversity.

Overall, the obtained findings reveal that deep learning–based object detection approaches have high potential in detecting complex microscopic damage types such as sunn pest feeding

damage. The developed system produced results with the speed, consistency, and accuracy capable of replacing manual inspection in agricultural quality control processes and can be further strengthened in the future with larger datasets, different lighting conditions, and multi-sensor data.

ACKNOWLEDGMENT

This work was supported by the TÜBİTAK 1005 Project No. 124O724, titled “Development of an Integrated Wheat Quality and Foreign Material Analysis System”.

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VITENET: A NOVEL APPROACH FOR CLASSIFYING GALAXY MORPHOLOGY

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ABSTRACT

Identifying the morphology of galaxies is essential for comprehending their structural characteristics and evolutionary mechanisms. This assessment elucidates the evolution of the universe's large-scale structure by disclosing star formation rates, mass distribution, and galaxy interactions. This study introduces a hybrid methodology for the morphological categorization of galaxies by integrating EfficientNet and Vision Transformer models with SVM. The Galaxy Zoo 2 collection, comprising high-resolution and intricate galaxy pictures, was sourced from multiple origins and preprocessed for feature extraction. Prominent characteristics are derived from the dataset utilizing EfficientNet and ViT models and categorized using Support Vector Machines (SVM). The models' performance was assessed using accuracy, precision, recall, and F1-score. Other feature selection techniques, including ElasticNet (ENet), MRMR, Correlation (Corr), NCA, and Relieff, were utilized to refine the feature set before classification. The findings indicated that ENet consistently attained the maximum accuracy across various ViT and EfficientNet settings, with the ViT_large_32 model reaching an accuracy of 78.17%. The study indicates that EfficientNet models enhance processing speed, whereas ViT models augment classification performance by capturing more intricate information. Moreover, the pivotal function of feature selection algorithms in enhancing overall classification accuracy is underscored.

Keywords: Astronomical image, vision transformers, feature reduction

1. INTRODUCTION

1.1. Background

Research in space and astronomy is crucial to humanity's quest to comprehend the universe. Prolonged interest and curiosity in space have resulted in a growing number of studies in this domain. These studies elucidate the origin, structure, and future of the universe. Astronomy elucidates the universe's fundamental nature by examining stars, galaxies, planets, and other celestial entities. Conversely, space studies hold significant value for technology advancements and discoveries. Space exploration facilitates the advancement of innovative technology. Advanced research is conducted in satellite technologies, communication, meteorology, navigation, and environmental monitoring. Research in space and astronomy is crucial for humanity's future, contributing to scientific and technical advancements, and is regarded as a priority by global scientific communities.

The classification of astronomical images using artificial intelligence is transforming the domains of astrophysics and cosmology. The extensive data produced by telescopes and space observatories is beyond the capacity for analysis using conventional approaches. Analyzing and categorizing this data presents a significant possibility for enhanced comprehension of the universe. Nonetheless, the manual analysis of extensive data sets is arduous and time-intensive [1]. Incorporating artificial intelligence and deep learning methodologies enables astronomers to evaluate data more rapidly and effectively.

Artificial intelligence and deep learning models are crucial for the automated classification of astronomical data. Deep learning models facilitate identifying and categorizing galaxies, stars, planets, and other celestial entities, achieving far higher accuracy rates than conventional techniques. These models enable novel discoveries and enhance comprehension of the universe's structure. Consequently, deep learning and artificial intelligence-based categorization techniques substantially advance scientific endeavors by facilitating innovation and discoveries in astronomy. Deep learning techniques, particularly Convolutional Neural Networks (CNNs) and, more recently, Vision Transformer (ViT) models, have gained prominence in the classification of celestial imagery. CNNs yield superior outcomes in image data processing and feature extraction, but ViT models are adept at comprehending long-range relationships inside images. Moreover, integrating these models with diverse machine learning techniques, such as employing ViT for feature extraction and classification using models like SVM, significantly enhances classification accuracy in astronomical data. These advancements enable astronomical study to be more thorough and expedient, facilitating the finding of new insights into the cosmos.

The morphological classification of galaxies, based on their visual attributes and conducted in this work, is crucial in the domains of astronomy and astrophysics. This categorization offers insight into the universe's evolution by examining galaxies' structural features. The shapes, sizes, colors, and structural elements of galaxies (such as spiral arms, bar structures, and ring or lenticular forms) offer insights into their genesis and evolution. Morphological classification enhances our comprehension of galaxy formation, interactions, and evolutionary processes.

Morphological classification is a foundation for examining several features of galaxies, including their star formation rates, mass distributions, and the influence of supermassive black holes at their cores. Spiral galaxies are typically recognized for their elevated star formation rates, whereas elliptical galaxies have been noted to exhibit reduced star formation rates. This information evidences that galaxies exhibit remnants of historical mergers and interactions.

The morphological classification of galaxies is pivotal in cosmology. It is an essential instrument for comprehending the history and future of the universe.

1.2. Motivation

The morphological classification of galaxies has a lengthy research history in astronomy and astrophysics, significantly contributing to comprehending the universe's structure and dynamical features. The study of this domain commenced with Edwin Hubble's establishment of spiral, elliptical, and irregular classification systems for galaxies in the 1920s, subsequently advancing through the creation of more intricate and comprehensive classification frameworks. Hubble's fundamental categorization system offered the initial comprehensive framework based on the structural characteristics of galaxies, and numerous subsequent investigations have enhanced and refined it. Contemporary technology and telescopic views enable a more detailed examination of the morphological characteristics of galaxies, while computerized image processing and artificial intelligence methodologies have significantly expedited the classification process. This literature review thoroughly examines the historical evolution of the morphological classification of galaxies predicated on their visual characteristics, current methodologies, and recent progress in this domain.

In recent years, research has focused on utilizing deep learning methodologies for image analysis, classification of stars and galaxies, galactic morphology, and the identification of merging galaxies. Subsequently, comparisons were conducted among several deep learning models, and transfer learning research was applied to identify distinct issues. [2], [3], [4], [5], [6], [7], [8].

In 2021, Moonzarin Reza utilized Sloan Digital Sky Survey (SDSS) data and employed automated machine learning (AutoML) methodologies to categorize galaxy shapes [9]. The approach explicitly integrates neural networks and machine learning methods to address galactic mergers and other complex categorization challenges. The study achieved exceptionally high accuracy rates by analyzing artificial neural networks and techniques like ExtraTrees. The classification accuracy of artificial neural networks was 98.2%, whereas the ExtraTrees technique attained 97.5% accuracy. The results demonstrate the efficacy of AutoML in galaxy classification. In a 2022 study, Şenel employed CNN for the morphological classification of galaxies [10]. The research utilized the Galaxy10 dataset from the Sloan Digital Sky Survey. To enhance the performance of the CNN, three distinct meta-heuristic methods were employed: Grey Wolf Optimizer (GWO), Particle Swarm Optimization (PSO), and Artificial Bee Colony (ABC). The study's results indicated that the highest accuracy rate was achieved with GWO. This approach achieved an accuracy rate of 85% on the test data and 93% on the training data. In comparison to alternative algorithms, they yielded the most successful outcomes.

In 2022, Eassa et al. performed morphological classification research by examining the luminosity data from the pictures of galaxies in the EFIGI dataset [11]. Their suggested algorithm employs an innovative brightness thresholding technique to pinpoint the centers and areas of galaxies, subsequently classifying them according to brightness changes. Upon conclusion of the trial, a success rate of 97.2% was attained. The average time taken to classify each galaxy was 0.37 seconds. In a separate study from the same year, Kwik et al. examined the components of the UGC 2885 galaxy utilizing machine learning [12]. The research sought to categorize distinct elements (young star population, old star population, dust lanes, galactic center, outer disk, and sky background) of a substantial spiral galaxy such as UGC 2885 at the pixel level. The Maximum Likelihood Classifier (MLC), Random Forest (RF), and Support Vector Machines (SVM) were employed for this objective. The SVM model demonstrated the

highest performance, achieving an accuracy of 84.9%. The RF model attained 82.6%, while the MLC model exhibited the least success relative to the others. The work presents a new approach highlighting the significance of textural properties for improved classification of small-scale cosmic formations.

In 2023, Wang et al. categorized over 49,000 emission line galaxies recorded by the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) [13]. Four distinct machine-learning techniques were employed for the spectral classification of galaxies: Multi-Layer Perceptron (MLP), Support Vector Machines (SVM), K-Nearest Neighbor (KNN), and Random Forest (RF). The classification approach utilized spectral flux pixels surrounding frequently employed emission lines as the feature space. The results indicate that MLP achieved the highest accuracy rate of 92.31%. The studies are summarized in Table 1.

In 2024, Xue-qi et al. concentrated on the automated identification of Low Surface Brightness Galaxies (LSBGs) via the YOLOX-CS algorithm [14]. The study evaluated five distinct classical target identification methods for identifying LSBGs, which exhibited enhanced performance relative to these algorithms. The use of DCGAN yielded a recall of 97.75% and an average precision of 97.83% on augmented datasets. The findings indicate that the YOLOX-CS algorithm is an effective approach for identifying LSBGs and is applicable in extensive sky surveys.

Tablo 1. *Related Works*

Year	Authors	Study	Dataset	Results
2021 [9]	Moonzarin Reza	Artificial Neural Network and ExtraTrees	Galaxy Zoo	Acc 98.2% Acc 97.5%
2022 [10]	Fatih Ahmet Şenel	CNN, GWO,	Galaxy10 Sloan Digital Sky Survey (SDSS)	Acc 85%
2022 [11]	Mohamed Eassa, Ibrahim Mohamed Selim, Walid Dabour, Passent Elkafrawy	A new brightness thresholding method	EFIGI	Acc 97.2%
2022 [12]	Robin J. Kwik, Jinfei Wang, Pauline Barmby, Benne W. Holwerda	Components of the galaxy UGC 2885	MLC, RF ve SVM	Acc 84.9% Acc 82.6%
2023 [13]	Li-Li Wang, Wen-Yan Zheng, Li-Xia Rong, Guang-Jun Yang, Jun-Liang Zhang, Yan-Hong Xie, Wen-Bo Wang, Li-Min Zhao	MLP, SVM, KNN ve RF	About 49000 emission line galaxies observed by LAMOST	Acc 92.31%
2024 [14]	Feng Xue-qi, Tu Liang-ping, Zhong Zheng-di, Li Juan, Li Xin	YOLOX-CS, DCGAN	SDSS DR16	97.75% recall 97.83% AP

1.3. Contributions

This study's primary contributions can be encapsulated as follows:

- Vision Transformer (ViT) models were employed for direct classification and feature extraction, demonstrating enhanced classification accuracy relative to EfficientNet models.
- Feature selection was conducted on the features extracted with ViT utilizing ElasticNet, followed by SVM classification. This procedure markedly lowered the dimensionality of the feature space while enhancing both precision and processing efficiency.
- The amalgamation of ViT, ElasticNet's feature selection, and SVM's classification techniques enhanced classification efficiency, yielding excellent accuracy rates while markedly decreasing processing durations.

This study offers a significant methodological framework to investigate and enhance the integration of deep learning and machine learning techniques for galaxy morphology classification. It presents a thorough approach that enhances feature extraction and classification in terms of efficiency and precision.

1.4. Organization

The initial segment of the study discusses space and astronomy research while summarizing relevant material. The second section elucidates the data set employed in the study and the methodologies utilized. This section provides a detailed explanation of the study's planned methodology. The third section delineates the experimental results derived from the investigation. Ultimately, a summary and prospective studies are addressed.

2. MATERIALS AND METHOD

2.1. Dataset

This study utilized the Galaxy Zoo 2 dataset [15]. Galaxy Zoo 2 is a publicly accessible dataset utilized for astronomical study, concentrating on the morphological classification of galaxies. The Galaxy Zoo 2 initiative facilitates the categorization of galaxy photographs by volunteer citizen scientists. The data is from the Sloan Digital Sky Survey (SDSS) pictures. This project builds upon Galaxy Zoo and has been enhanced to investigate further the galaxies observed in the universe. The Sloan Digital Sky Survey (SDSS) is an initiative that has surveyed an extensive portion of the sky and documented millions of galaxies. Galaxy Zoo 2 utilizes high-resolution photos from the SDSS.

The project comprises photos of over 300,000 galaxies. These galaxies typically possess a redshift value below 0.25, indicating their proximity to us. Volunteers worldwide have researched and classified the galaxies in Galaxy Zoo 2. Volunteers assist in identifying the morphological traits of each galaxy. Users categorize galaxies into distinct classifications. The primary morphological types encompass spiral, elliptical, lenticular, and irregular forms. Furthermore, classifications extend beyond fundamental categories. Volunteers have also discerned intricate characteristics such as bar structure in barred spiral galaxies, the quantity and direction of spiral arms, core density, and collision signs.

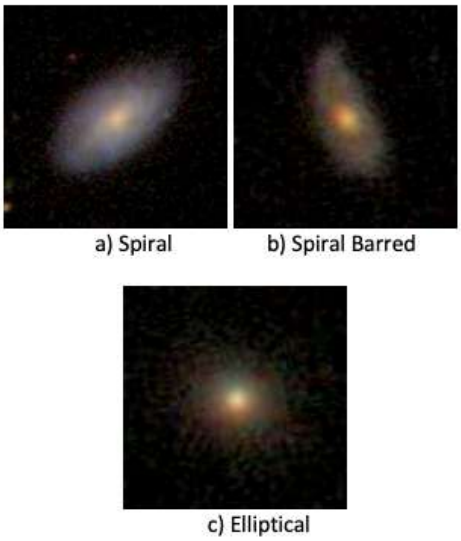

Figure 1. *Samples of Dataset*

The dataset included in the study comprises three classes: elliptical, spiral, and barred spiral. The classifications are categorized according to the morphological classification of the galaxies. Elliptical galaxies possess a round or oval morphology. They typically contain less dust. Minimal to no new stellar formation occurs. Aged stars characterize them and lack discernible structural features. Spiral galaxies possess a disk configuration featuring a central nucleus and spiraling arms that revolve around it. New star formation is typically vigorous, and these galaxies comprise both ancient and youthful stars. Barred spiral galaxies resemble spiral galaxies yet possess a bar traversing the central core. This bar spreads radially from the galactic center outward. Spiral arms radiate from the termini of this bar. These classifications are extensively employed in the Hubble sequence to delineate the morphological characteristics of galaxies. Although the aggregate data across three classes is substantial, it was standardized to 9,000 entries per class to ensure equilibrium in the dataset utilized for the study.

2.2. Feature Extraction with EfficientNet and Vision Transformers

2.2.1. EfficientNet

Google developed EfficientNet, a deep learning model based on Convolutional Neural Networks (CNN). The model scales proportionately with three primary parameters: width, depth, and resolution. This yields a more efficient architecture while simultaneously attaining elevated accuracy rates. EfficientNet is a network architecture that demands reduced computational resources while delivering superior performance via optimal utilization of model parameters.

The EfficientNet design consists of a series of MBConv blocks built and enhanced from the MobileNetV2 architecture [16], [17]. The latest iteration of the EfficientNet model is V2. This study employs the EfficientNet V2 Small, EfficientNet V2 Medium, and EfficientNet V2 Large models. EfficientNet V2 Small represents the smallest variant within the V2 family. This model is optimized for limited data sets and reduced computational power demands. In contrast to the original EfficientNet, the EfficientNet V2 series provides expedited and more efficient training with training-aware neural architecture search (NAS). EfficientNet V2 Small is distinguished by its rapid training duration and minimal computing expense while delivering acceptable accuracy on extensive data sets. The mid-tier variant of the EfficientNet V2 family is the EfficientNet V2 Medium model. This model delivers an equilibrium of computing

capability and precision. The model featuring increased layers and width delivers a harmonious performance regarding accuracy and computational duration and is employed in applications like categorization and object identification. EfficientNet V2 Large is the most substantial model within the series. Its extensive architecture is geared for processing high-resolution photos and extracting intricate features. This work employs the EfficientNet architecture to examine the dataset's high-dimensional and complicated structure through comprehensive feature extraction. This method yields a high accuracy rate in the classification of galaxy morphology.

2.2.2. Vision Transformers (ViTs)

Vision Transformers employ a purely transformer design rather than convolutional neural networks for computer vision tasks, including picture categorization. Transformer models were originally designed for natural language processing (NLP) problems, and the ViT model has effectively applied this architecture to image processing. The primary distinction is that rather than generating feature maps as in conventional CNNs, ViT segments images into patches, treats each patch as an array, and subsequently inputs these arrays into the transformer layers accordingly [18].

ViT segments the input image into small patches of predetermined dimensions. This procedure is referred to as Patch Embedding. Each particle is depicted as a collection of vectors analogous to word vectors in conventional natural language processing. A 224x224 pixel image is segmented into 196 segments of 16x16 pixels. The image segments are augmented with positional data to align with the transformer models' inherent sequential processing framework [19]. The location of each segment conveys critical information for the model to comprehend the interrelations among the segments.

The primary element of transformers is the multi-head self-attention mechanism [20]. This method acquires significant information by focusing on various areas of the image. These layers ascertain the interrelations among image segments and progressively refine the derived attributes. After the transformer layers, the output is directed to a classification layer. This layer generates an output that signifies the class labels.

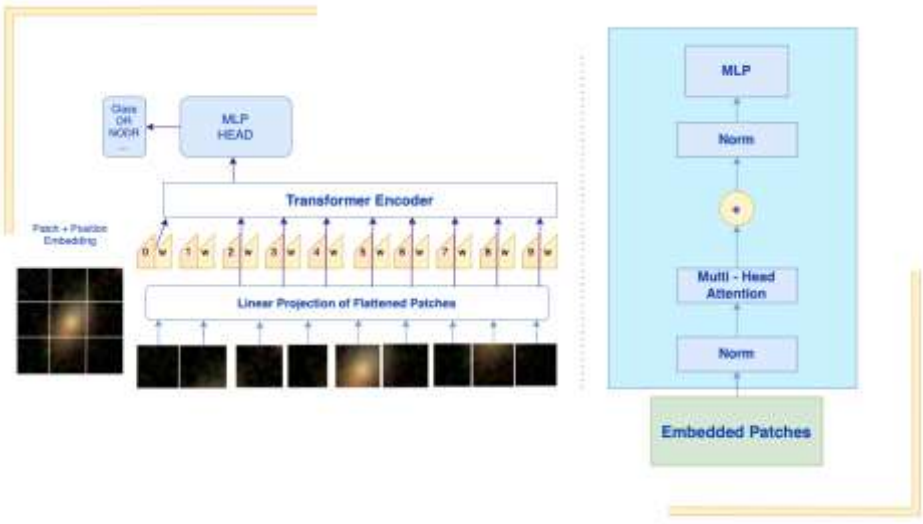

Figure 2. *Architecture of ViT*

The ViT models employed in the study vary in size, each optimized for a particular resolution and dimension. The study employs two distinct ViT architectures: ViT Base 16/32 and ViT

Large 16/32. ViT Base is one of the fundamental iterations within the ViT family. This model segments the input image into small blocks of 16x16 and 32x32 and processes each block through transformer layers. This model possesses limited parameters and is efficient for small to medium-sized datasets. It is mainly utilized in classification tasks that want high precision but do not demand extensive data sets. The ViT Large model is an expanded version of the model. It is optimized for extensive data sets and incorporates additional parameters.

2.3. Feature Selection with ElasticNet

Feature selection is a technique that aims to eliminate redundant or low information value features from a data set. The process aims to simplify the model and reduce the computational cost while improving the performance of the model. Redundant features can cause noise in the model's learning process, leading to model overfitting and reduced accuracy. Feature selection increases the accuracy and reduces the processing time by working with less but meaningful data.

In this study, feature selection is necessary because of the large number of features extracted with ViT models. ViT models are capable of extracting high-dimensional and detailed features for the morphological classification of galaxies. However, including all of these features in the classification model increases the computational cost and may lead to overfitting of the model. In particular, the features extracted by powerful models such as ViT can be very large and complex, leading to the inclusion of redundant or low-information features.

This work employed ElasticNet to minimize the feature set derived from ViT, retaining only the most significant characteristics of the model. ElasticNet regulates the high correlation among features, identifies the most significant ones, and incorporates superfluous features, hence enhancing the model's efficiency and performance. Consequently, only the features retrieved with ViT that significantly enhance classification have been picked, resulting in a substantial reduction in processing time and an improvement in classification accuracy.

ElasticNet is a linear regression model employed for feature selection and regression tasks. It functions as an amalgamation of Lasso (L1 norm) and Ridge (L2 norm) regressions [21]. ElasticNet mitigates the limitations of Lasso in the presence of significant data correlation, hence yielding a more resilient model. ElasticNet employs both L1 and L2 penalties, enabling stringent constraints on feature selection while permitting minor yet significant characteristics to persist in the model. The punitive procedure employs a blend of L1 and L2 norms, resulting in the reduction of certain model features to zero while retaining others, thereby eliminating superfluous parameters and preserving just the essential ones. The primary purpose of employing ElasticNet in the study is to efficiently select high-dimensional characteristics derived from the ViT model and exclude superfluous ones. The application of ElasticNet has diminished the number of features derived from ViT, enhancing the model's speed and efficiency while reducing processing time and complexity.

2.4. Classification with Support Vector Machine (SVM)

Classification is the process of categorizing items or observations within a collection into specific classes. Classifying each image in a dataset into categories, such as "galaxy" or "star," constitutes a classification task. Classification is employed to interpret data and facilitate automatic processing, playing a crucial role, particularly in image processing, medical diagnostics, biometric recognition, and various other domains. Classification algorithms forecast new data based on acquired characteristics, hence expediting and automating decision-making processes. This study utilized EfficientNet and ViT models to extract attributes for the categorization of galaxy morphological characteristics, which were further classified using

Support Vector Machines (SVM). This study employed classification to ascertain the morphological class of each galaxies based on the data analysis. The ViT and EfficientNet models extracted intricate and high-dimensional information from the photos, enabling the classification algorithms to categorize the galaxies into distinct morphological classes. The categorization method has facilitated the efficient processing of big datasets through precise and rapid predictions.

Support Vector Machine (SVM) is a supervised learning technique commonly employed in classification tasks. SVM seeks to identify the broadest margin between the data to separate it into two distinct classes. This marginal December is referred to as the hyperplane, which delineates the data. Support vectors are the nearest data points to the hyperplane and dictate categorization outcomes [23]. This study favors SVM for classifying attributes derived from EfficientNet and ViT models. The ViT and EfficientNet models meticulously extracted the morphological characteristics of the galaxies, while the SVM facilitated the categorization of this higher-dimensional data with greater efficiency and accuracy. Support Vector Machines (SVM) are favored for their rapid and precise classification capabilities, particularly in extensive and intricate data sets. The kernel functions of the SVM have significantly enhanced the categorization of nonlinear and complex galaxy data. The kernel functions of SVM have offered an optimal approach for identifying nuanced distinctions among galaxies, enhancing the Declaration process's speed and efficiency.

2.5. Proposed Method

This work proposes a method that integrates deep learning with classic machine learning approaches for the morphological categorization of galaxies. Currently, deep learning models are employed to get elevated accuracy levels in intricate tasks such as picture classification and feature extraction. Nonetheless, in the context of high-dimensional and intricate datasets, redundant or excessively informative features might detrimentally impact model performance. Consequently, an extra feature selection and classification phase is necessary for the more effective processing of features derived from deep learning models. This study optimizes features extracted by deep learning models, including EfficientNet and ViT, utilizing SVM and ElasticNet to enhance classification accuracy. Figure 3 presents a summary of the work.

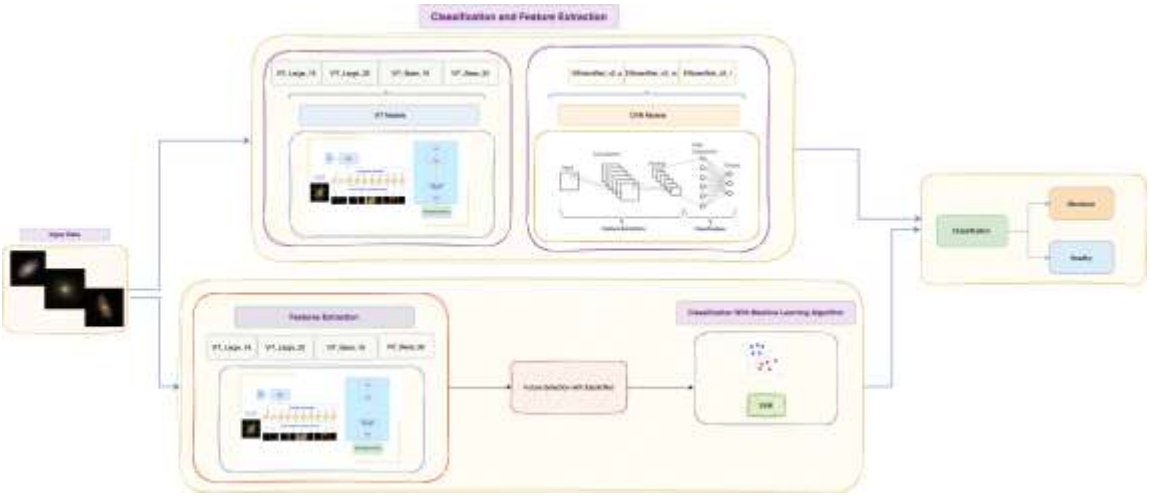

Figure 3. *Proposed Method*

The morphological classification of the galaxies was conducted utilizing EfficientNet and ViT models. EfficientNet models provide an effective classification mechanism by proportionately

scaling breadth, depth, and resolution. These models examine visual details with great precision by extracting features from several layers of the data. The classification performance and processing time of various EfficientNet versions (B7, V2 S, V2 M, V2 L) were assessed. At this juncture, the classification accuracy of each model was evaluated to ascertain which model yields more effective outcomes. Conversely, ViT models analyze images in segments, transforming each segment into an array and deriving characteristics from these arrays through a multi-head attention mechanism. ViT yields successful outcomes in intricate data sets, particularly because of its capacity to comprehend long-range relationships. Both EfficientNet and ViT models attained elevated accuracy rates in the classification task; however, ViT demonstrated enhanced performance on bigger and more intricate data sets. This phase illustrated the efficacy and precision of the deep learning models employed for the fundamental classification procedure.

Subsequently, deep learning models, including EfficientNet and ViT, are employed for feature extraction on the galaxy morphology dataset. EfficientNet and ViT models excel at extracting intricate features from high-resolution and complex images. EfficientNet is an efficient convolutional neural network, whereas ViT is founded on transformers and adept at learning long-range dependencies. The features derived from these two models are utilized to interpret the morphological structure of the images.

Subsequent to feature extraction, these features were classified using Support Vector Machine (SVM) methodology. Support Vector Machine (SVM) is a classification technique that excels in high-dimensional data scenarios. The intricate and high-dimensional features derived by ViT and EfficientNet were categorized with greater efficiency and accuracy. Due to the potential poor information value or noise of many retrieved features in the dataset, feature selection was conducted using ElasticNet. ElasticNet integrates Lasso and Ridge regression techniques, enhancing performance by removing redundant features while retaining significant ones in the model. This is an essential measure to enhance the model's speed while simultaneously improving classification accuracy.

The features identified by ElasticNet are subsequently classed using SVM. This procedure enhances categorization by enabling the model to utilize fewer, however more significant, characteristics. The ultimate classification phase is to precisely categorize the morphological structures of the galaxies. This approach integrates deep learning and machine learning techniques, facilitating precise classification of extensive and intricate datasets.

3. EXPERIMENTAL RESULTS

This research examines the efficacy of EfficientNet and ViT models in a galaxy morphological classification problem. The discussion focuses on the comparison of accuracy rates, processing speeds, and overall efficiency of both models, particularly the impact of feature selection and classification using ElasticNet on model performance. The study findings elucidate the benefits and drawbacks of various methodologies and specify which methodology yields the most favorable outcomes.

The initial phase of the project employed EfficientNet models to conduct traditional classification on the galaxy morphology dataset. Table 2 presents the accuracy rates and processing speeds of the three distinct EfficientNet models. This data allows for comparing the models' efficient categorization capabilities and performance.

Table 2. *Traditional Classification Results with EfficientNet Models*

	EffcientNet_v2_s	EffcientNet_v2_m	EffcientNet_v2_l
Accuracy (%)	75.64%	61.13%	77.1%
Time (sec)	18850 sec	32500 sec	60750 sec

The galaxy morphology dataset comprises a sophisticated collection of high-resolution photographs. EfficientNet models are optimized deep learning architectures intended to classify intricate pictures. EfficientNet models aim to enhance both efficiency and accuracy by optimizing parameters, including width, depth, and resolution. The dataset utilized in this work comprises a vast and varied collection of photos, rendering precise classification rather difficult. Consequently, the efficacy of any model is of paramount significance.

Table 1 presents the outcomes of the conventional categorization employing EfficientNet models in the initial part of the investigation. The accuracy rate and processing time are evaluated for each model. The dataset employed for the morphological categorization of galaxies comprises intricate and high-resolution photos. EfficientNet models exhibit varying performance in classification tasks in terms of accuracy and processing time. The Efficient_v2_s model demonstrates a reasonable performance, with an accuracy of 75.64%. The model accurately classifies the photos in the dataset but exhibits marginally inferior performance relative to other models that attain superior accuracy. This model exhibits rapid processing capabilities, yielding results more swiftly than larger models, with a completion time of 18,850 seconds. The EfficientNet_v2_m model had the lowest accuracy, with 61.13%. The diminished accuracy signifies that the model encounters difficulties in comprehending the intricate structures within the dataset, resulting in subpar performance on the classification job. The processing duration is 32,500 seconds, exceeding that of the EfficientNet_v2_s model, although the accuracy is inferior. This indicates that the model lacks efficiency. The EfficientNet_v2_l model exhibits the greatest accuracy rate of 77.1%. This indicates that the model is more proficient at processing and classifying the dataset. Nonetheless, this enhanced precision is accompanied by an extended processing duration. The processing duration is 60,750 seconds, indicating that this model possesses a complicated and intricate architecture. The model's elevated correctness necessitates increased resources regarding computational expense and duration.

The EfficientNet models provide varying degrees of accuracy and processing durations on this dataset. The EfficientNet_v2_l model provides the greatest accuracy but has the longest processing duration. Conversely, EfficientNet_v2_s is the most rapid model regarding processing time and provides modest accuracy. EfficientNet_v2_m is the least efficient model, exhibiting both diminished accuracy and comparatively extended processing duration. Table 2 delineates the strengths and drawbacks of each model, facilitating the selection of the appropriate model for classification tasks.

Table 3. *EfficientNet Evaluation Metrics Results*

	EffcientNet_v2_s	EffcientNet_v2_m	EffcientNet_v2_l
Precision	91.24%	82.36%	90.34%
Recall	81.89%	69.97%	84.47%
F1 – Score	86.3%	75.65%	87.3%

The evaluation findings in Table 3 indicate that the EfficientNet_v2_s model has a balanced performance, achieving 91.24% precision and 81.89% recall, with an F1-score of 86.3%. The EfficientNet_v2_m model exhibits the lowest performance, achieving a precision of 82.36%, a recall of 69.97%, and an F1 score of 75.65%. The EfficientNet_v2_l model has the greatest F1 score at 87.3%, with a precision of 90.34% and a recall of 84.47%. The results indicate that the EfficientNet_v2_l model provides superior accuracy and stability, while the EfficientNet_v2_m model exhibits subpar performance.

The complexity matrices of the data acquired in the investigation are illustrated in Figure 4.

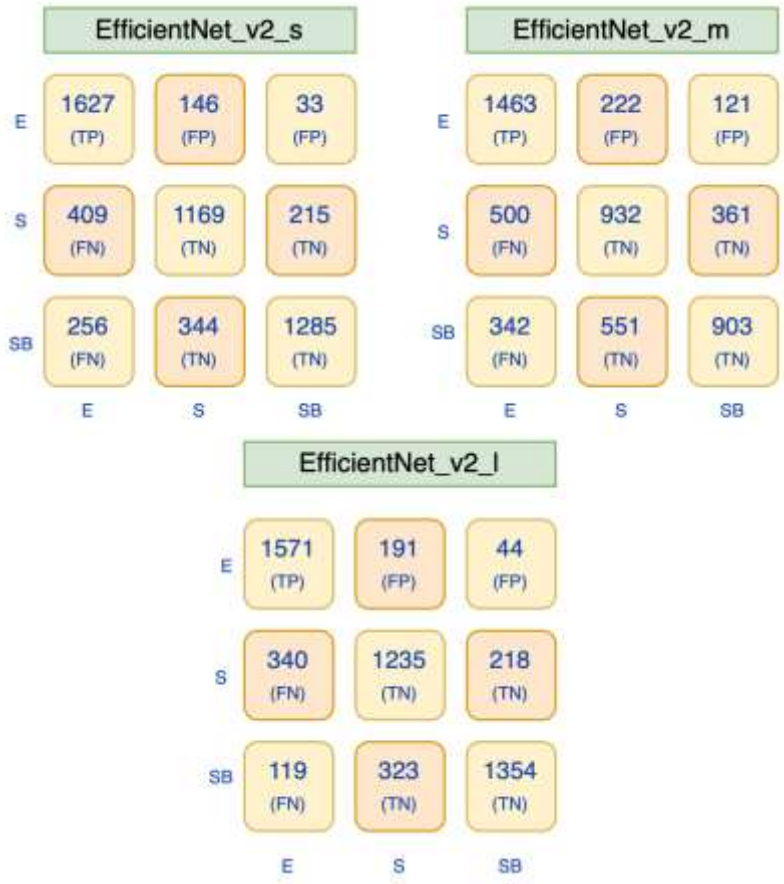

Figure 4. *Confusion Matrices of EfficientNet Traditional Classification*

In the subsequent phase of this project, EfficientNet models were employed for classification and extracting significant features from the dataset. EfficientNet's intricate layered architecture meticulously examined the physical characteristics of the galaxies and derived high-dimensional, rich feature vectors from each image. The features obtained at this stage are subsequently employed in the classification phase via a machine learning method known as SVM to enhance model performance. The feature extraction by EfficientNet enhanced the model's comprehension of intricate aspects in the dataset, hence augmenting overall classification accuracy.

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SVM to enhance model performance. The feature extraction by EfficientNet enhanced the model's comprehension of intricate aspects inside the dataset, hence augmenting overall classification accuracy.

Table 4 illustrates that the features extracted using EfficientNet models were classified with SVM, including the accuracy rates and processing times for each model. The EfficientNet_v2_s model exhibits the least performance, with an accuracy of 67.36%. Nonetheless, the processing duration is the most prolonged at 11558. This outcome suggests that the extended runtime of the model, notwithstanding its diminished accuracy, is attributable to the intricacy of the feature extraction procedure. The EfficientNet_v2_m model achieved an accuracy rate of 67.61% and exhibited the fastest processing time at 4071.80 seconds. The model's inability to deliver high accuracy despite its rapid execution indicates that the derived features may lack sufficient discriminative power. The EfficientNet_v2_l model had the highest performance, with an accuracy of 69.44%. The processing speed of this model is exceptionally rapid at 3991 seconds. The results indicate that the EfficientNet_v2_l model yields greater accuracy in a shorter duration, albeit its increased complexity.

Table 4. *EfficientNet ile özellik seçimi ve SVM sınıflandırma*

	EffcientNet_v2_s	**EffcientNet_v2_m**	**EffcientNet_v2_l**
Accuracy (%)	67.36%	67.61%	69.44%
Time (sec)	11558 sec	4071.80 sec	3991 sec

The high-resolution and complicated nature of the galaxy morphology dataset utilized in this study renders the feature extraction efficacy of EfficientNet models crucial. Specifically, EfficientNet_v2_l epitomizes the best balanced and efficient model regarding accuracy and processing time.

Table 5. *Evaluation Metrics Results of EfficientNet Feature Extraction and SVM Classification*

	EffcientNet_v2_s	**EffcientNet_v2_m**	**EffcientNet_v2_l**
Precision	67.1%	67.35%	69.44%
Recall	67.36%	67.61%	69.43%
F1 – Score	66.94%	67.08%	69.43%

Table 5 presents the precision, recall, and F1-score metrics achieved following feature extraction using EfficientNet models and classification by SVM. The EfficientNet_v2_s model attained a precision of 67.1%, a recall of 67.36%, and an F1 score of 66.94%. The EfficientNet_v2_m model yielded marginally more balanced outcomes, achieving 67.35% precision, 67.61% recall, and 67.08% F1-score. The EfficientNet_v2_l model achieved the highest performance with 69.44% precision, 69.43% recall, and a 69.43% F1 score. The results indicate that the EfficientNet_v2_l model excels in feature extraction and classification, yielding more balanced outcomes relative to other models. Figure 5 illustrates the confusion matrix of the investigation.

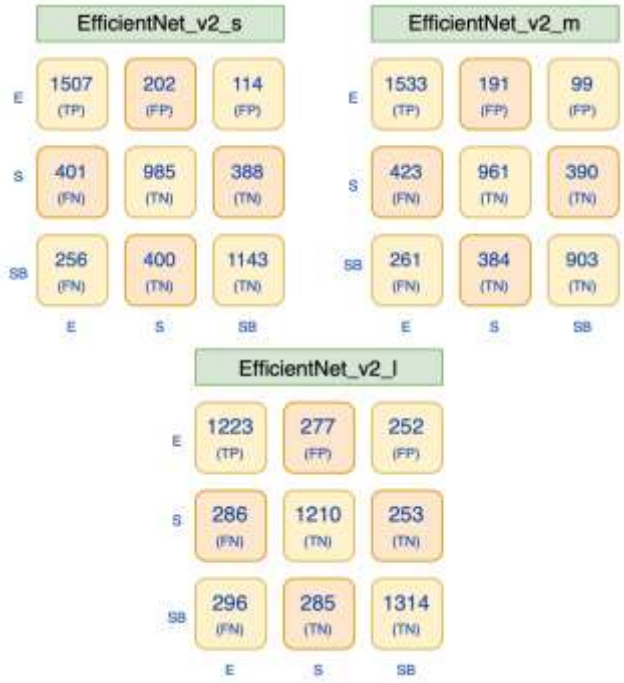

Figure 5. *Confusion Matrices of EfficientNet Feature Extraction and SVM Classification*

In another segment of the investigation, conventional categorization was conducted utilizing ViT models. Table 6 presents the classification outcomes of this segment of the investigation. The accuracy rate and processing time are evaluated for each model. The dataset of galaxy morphology comprises high-resolution and intricate photos. ViT models employ a transformer-based methodology to examine this information and achieve precise classifications. The ViT_base_16 model has the best accuracy and effectively classifies the photos within the dataset. The processing time of this model is considerable (40,700 seconds), indicating that its intricate architecture and complicated transformer design incur substantial computational expenses. The ViT_base_32 model exhibits marginally inferior performance on the classification challenge, with an accuracy of 70.43%. Nonetheless, the processing time is relatively swift (13150 seconds), suggesting that the model possesses a streamlined architecture capable of yielding quicker outcomes. Reduced accuracy indicates that the model captures less detail; however, its speed advantage renders it preferable for some projects. The ViT_large_16 model exhibits an accuracy of 70.47%, comparable to that of the ViT_base_32 model. Nonetheless, the processing duration is rather lengthy (131,700 seconds). This outcome indicates that the model is inadequate regarding accuracy and necessitates considerable processing time. Consequently, it does not provide optimal performance regarding accuracy and processing time. The ViT_large_32 model attains an accuracy of 74.51% and operates more swiftly than the ViT_large_16 model (44700 seconds). This model provides a harmonious performance regarding precision and processing duration, rendering it an appropriate choice for extensive datasets.

Table 6. *Traditional Classification Results with ViT Models*

	ViT_base_16	ViT_base_32	ViT_large_16	ViT_large_32
Accuracy (%)	77.07%	70.43%	70.47%	74.51%
Time (sec)	40700 sec	13150 sec	131700 sec	44700 sec

ViT models possess the ability to capture long-range correlations through transformer design on these datasets. The ViT_base_16 model exhibits the maximum accuracy; nonetheless, it incurs significant processing time costs. The ViT_base_32 type operates at the highest speed, but with marginally reduced accuracy, yet it offers the benefit of rapid performance. ViT_large_32 provides a more equitable performance, yielding satisfactory outcomes in both accuracy and processing duration.

Table 7. *ViT Traditional Classification Evaluation Metrics Results*

	ViT_base_16	ViT_base_32	ViT_large_16	ViT_large_32
Precision	77.63%	70.43%	70.47%	74.5%
Recall	77%	72.3%	71.2%	75.07%
F1 – Score	77.31%	71.35%	70.83%	74.78%

The outcomes presented in Table 7 are assessed based on the precision, recall, and F1-score metrics of conventional classification utilizing ViT models. The ViT_base_16 model exhibits the highest F1-score of 77.31%, with precision at 77.63% and recall at 77%. The ViT_base_32 model achieves an F1 score of 71.35%, with a precision of 70.43% and a recall of 72.3%. The ViT_large_16 model attained an F1-score of 70.83%, with precision at 70.47% and recall at 71.2%. The ViT_large_32 model demonstrated a balanced performance, achieving a 74.78% F1-score, with 74.5% precision and 75.07% recall. The results indicate that ViT models exhibit varying capabilities in terms of precision and recall, with the ViT_base_16 model achieving the highest overall F1 score. The confusion matrices are depicted in Figure 6.

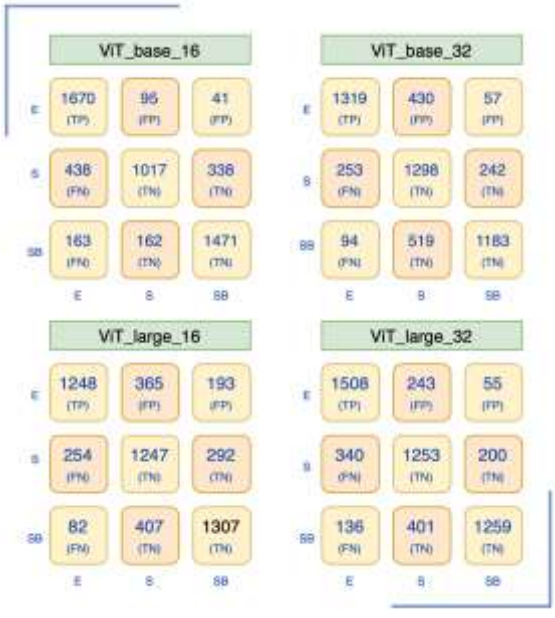

Figure 6. *Confusion Matrices of ViT Traditional Classification*

In another segment of the investigation, ViT models were employed for feature extraction. Table 7 presents the accuracy rates and processing durations derived from feature extraction utilizing ViT models and the subsequent categorization of these features with SVM. ViT models were utilized with SVM to extract features from intricate and high-dimensional images, facilitating faster and more efficient classification of these features.

The ViT_base_16 model exhibits modest performance, with an accuracy of 69.42%. The precision in feature extraction is satisfactory, if not exceptional. The processing time is longer than that of the other models (23834.67 seconds) due to the model's intricate structure and processing capabilities. The ViT_base_32 model has the lowest performance, achieving an accuracy of 66.72%. Nonetheless, its processing time is relatively swift (18559 seconds), indicating its suitability for tasks necessitating expedited results, but with marginally reduced accuracy. Despite its lack of accuracy, it is beneficial in scenarios that need rapidity. The ViT_large_16 model exhibits an accuracy of 69.05, which is comparable to that of the base models. The processing duration is also rapid (18559 seconds). This model delivers a harmonious performance regarding accuracy and processing duration, yielding beneficial outcomes within a realistic timeframe for extensive data sets. The ViT_large_32 model exhibits an accuracy of 66.68, comparable to that of the ViT_base_32 model. Despite being the largest configuration, this model has low accuracy. The processing duration is notably rapid (18559 seconds), facilitating prompt outcomes on intricate data.

Table 7. *Evaluation Metrics Results of ViT Feature Extraction and SVM Classification*

	ViT_base_16	**ViT_base_32**	**ViT_large_16**	**ViT_large_32**
Accuracy (%)	69.42%	66.72%	69.05%	66.68%
Time (sec)	23834.67 sec	18559 sec	18559 sec	18559 sec

The table illustrates that feature extraction using ViT models and classification via SVM are designed to enhance processing efficiency. Although the ViT_base 16 model achieves the maximum accuracy, its processing time exceeds that of the other models. The ViT_large_16 and ViT_large_32 models exhibit inferior accuracy compared to the ViT_base_16, despite their superior processing speeds. These findings can assist in selecting the appropriate model for tasks necessitating a balance between speed and precision.

Table 8. *Evaluation Metrics Results of ViT Feature Extraction and SVM Classification*

	ViT_base_16	**ViT_base_32**	**ViT_large_16**	**ViT_large_32**
Precision	69.2%	66.44%	66.44%	66.44%
Recall	69.42%	66.72%	66.72%	66.72%
F1 – Score	69.01%	66.32%	66.32%	66.32%

Table 8 presents the precision, recall, and F1-score metrics achieved following feature extraction using ViT models and classification by SVM. The ViT_base_16 model achieved the greatest F1 score of 69.01%, with a precision of 69.2% and a recall of 69.42%. The ViT_base_32, ViT_large16, and ViT_large_32 models produced comparable outcomes, achieving a precision of 66.44%, a recall of 66.72%, and an F1-score of 66.32%. The results indicate that the ViT_base_16 model demonstrates marginally superior performance compared to the other models, which exhibit comparable performance levels among themselves. The

primary explanation for the comparable performance of SVM in classifications with ViT models is because the characteristics derived from ViT models are highly analogous. The features derived from various ViT configurations are handled in a comparable manner by the SVM, and once the SVM attains a specific accuracy on high-dimensional data, minor model variations have minimal impact on performance. Moreover, the propensity of the SVM's kernel function to categorize analogous data similarly may contribute to the resemblance of the outcomes. The dataset's complexity, together with the analogous complexity of characteristics extracted by ViT models, also contributes to this issue.

The SVM is essential in this work for the rapid and precise classification of characteristics extracted by the ViT models. Support Vector Machines (SVM) facilitated the attainment of accuracies between 66% and 69% due to its proficiency in precise categorization, concurrently optimizing processing durations. The integration of ViT with SVM yielded precise and effective classification outcomes on extensive and intricate datasets. Figure 7 displays the confusion matrices of the investigation.

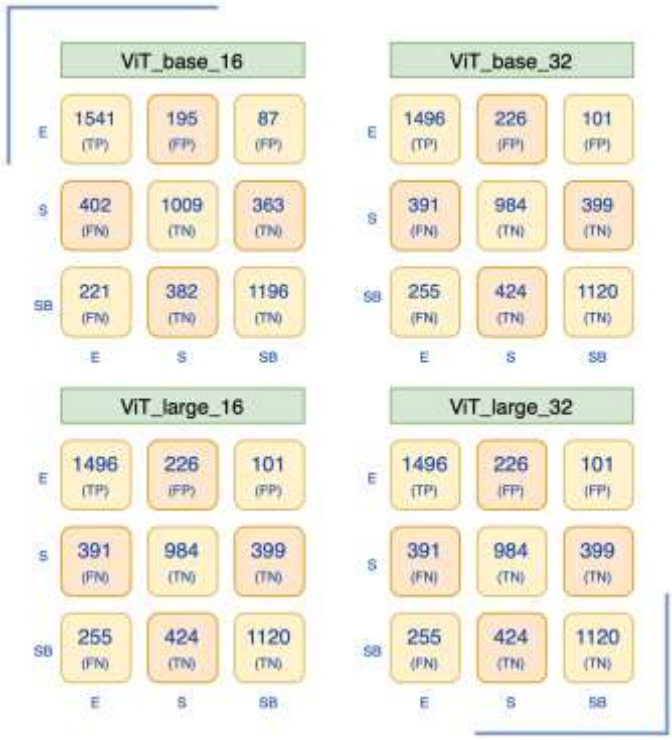

Figure 7. *Confusion Matrices of ViT Feature Extraction and SVM Classification*

In the final phase of the investigation, the features derived from the ViT models were categorized using the SVM algorithm in conjunction with several feature selection methods. Table 9 presents the accuracy ratios of features derived from the ViT models, optimized with various feature selection procedures and classed with SVM. The ViT_base_16 model attained the best accuracy of 69.94% with ElasticNet (ENet), whereas the lowest accuracy of 68.22% was obtained with the MRMR method. A like tendency was noted in the ViT_base_32 model, wherein the Enet method yielded the optimal results at 77.32%. This demonstrates Enet's efficacy in feature selection, discarding superfluous elements while retaining the essential ones. Other algorithms, particularly Corr and Relieff, exhibited comparatively low accuracy rates in the ViT_base_32 model, indicating that certain algorithms are inadequate for complicated data analysis.

Table 9. *Feature Selection results*

	ViT_base_16	ViT_base_32	ViT_large_16	ViT_large_32
Corr	69.23%	73.11%	68.33%	74.72%
ENet	69.94%	77.32%	70.19%	78.17%
MRMR	68.22%	72.38%	68.57%	74.62%
NCA	69.57%	73.08%	69.1%	75.99%
Relieff	68.44%	72.2%	68.22%	72.2%

The ViT_large_16 and ViT_large_32 models attained the best accuracies with Enet. ViT_large_32 exhibits the highest accuracy of 78.17 among all models. This outcome validates the efficacy of Enet on extensive and intricate datasets, demonstrating superior performance in classification with SVM. Among the various algorithms, MRMR exhibits the lowest accuracy for certain models; however, the accuracy of all models is generally comparable. Specifically, algorithms like Relieff and NCA yield satisfactory outcomes in certain models, whereas Enet distinctly emerges as the superior feature selection method. The Enet algorithm exhibits the shortest processing duration, totaling 1113 seconds. Figure 8 illustrates the complexity matrix of the most successful outcome.



Figure 8. *Complexity matrix of the highest result (1113 sec)*

4. CONCLUSION

This study employs EfficientNet and ViT models for feature extraction in the morphological classification of galaxies, with further classification performed using SVM. The results indicate that the robust feature extraction abilities of EfficientNet and ViT models enable the attainment of high accuracy rates in classifications using SVM. The ElasticNet algorithm's superior accuracy across all models underscores the essential importance of feature selection in classification efficacy. EfficientNet models yield quicker processing times, whereas ViT models deliver superior classification outcomes by extracting more intricate features. The benefits of both models across various datasets offer versatility in model selection.

Future research should conduct a comprehensive analysis of EfficientNet and ViT combinations on larger and more diverse datasets to enhance their performance. Furthermore, comparative analyses with alternative deep learning and machine learning methods can be performed to achieve more definitive outcomes about optimal model selection. Evaluating

novel transformer-based models and updated iterations of EfficientNet may enhance the conclusions of this research. Moreover, employing alternative classification algorithms in place of SVM can enhance the feature extraction procedure and elevate accuracy rates.

FUNDING INFORMATION

This project is supported by project number MF.24.24 within the scope of Fırat University Scientific Research Projects (FÜBAP).

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

DATA AVAILABILITY STATEMENT

The data supporting this study's findings are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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COMPARISON OF FILTER-BASED FEATURE SELECTION METHODS IN BREAST CANCER DIAGNOSIS USING MACHINE LEARNING

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ABSTRACT

Cancer is a serious health problem that threatens the lives of millions of people worldwide and can lead to death. Among women, breast cancer is one of the most common types of cancer, and if not detected early, it significantly increases mortality rates. Accurate and timely diagnosis enhances the effectiveness of treatment methods and prolongs patients' survival. In this context, the use of Machine Learning (ML) algorithms in medical diagnosis processes supports rapid and accurate decision-making. In this study, different combinations of filter-based feature selection methods and various ML algorithms were compared to determine the most successful combination for breast cancer detection. To support breast cancer diagnosis, several filtering methods (Information Gain (IG), Chi-square, Anova F, Relief, L1 Regularization, Correlation) were combined with Naive Bayes (NB), Support Vector Machines (SVM), Decision Trees, Artificial Neural Networks (ANN), Random Forest (RF), Logistic Regression (LR), XGBoost, and K-Nearest Neighbor (kNN) algorithms. These methods were applied to the Breast Cancer Wisconsin Data Set available on the Kaggle platform. For each combination of filtering method and ML algorithm, the accuracy rate were calculated and compared. The highest accuracy rate, 99.12%, was achieved with the AnovaF and ANN combination. This finding demonstrates that the joint use of appropriate feature selection and ML algorithms can significantly enhance performance in breast cancer diagnosis. Consequently, this study emphasizes that effective feature selection is a critical step in developing accurate and efficient medical decision support systems.

Keywords: Filter-Based Feature Selection, Breast Cancer, Machine Learning, Feature Selection, Artificial Neural Networks

1. INTRODUCTION

Cancer poses a serious threat to human health globally, with a significantly increased risk of death if it is not detected at an early stage. Breast cancer, one of the most common cancer types among women, leads to severe health complications and high mortality rates, particularly in its advanced stages. Therefore, early diagnosis and appropriate treatment strategies are of crucial importance in terms of patients' quality of life and survival outcomes. It is evident that efforts aimed at detecting the disease at an early stage hold great significance. In particular, studies examining ML applications for cancer types demonstrate that these methods offer substantial contributions to early diagnosis and the predictability of disease progression. ML algorithms systematically analyze available data, enabling the discovery of meaningful patterns and relationships within datasets. Moreover, they contribute to the development of computational models capable of effectively representing the data (Maita & Das, 2017).

The Breast Cancer Wisconsin dataset (UCI, 1995) is one of the most widely used datasets for breast cancer diagnosis. Bazazeh and Shubair (2016) compared SVM, RF, and Bayesian Network algorithms, reporting that SVM achieved the highest accuracy. Asri et al. (2016) identified SVM as the most successful method, with an accuracy of 97.13%, a low error rate, and high precision. Khourdifi and Bahaj (2018) further confirmed the reliability of SVM for diagnostic purposes, reporting 97.9% accuracy. Elsadig et al. (2023) achieved 97.7% accuracy with SVM using eight classifiers and five feature selection techniques. Singh et al. (2024) reported the best performance in terms of accuracy, sensitivity, and F1-score by employing hybrid feature selection methods. Lorencin et al. (2020) demonstrated that the performance of ANN depends on the size of the training dataset.

In this study, various feature selection techniques (IG, Chi-Square, ANOVA F-test, Relief, L1 Regularization, and Correlation) and a range of ML algorithms (NB, SVM, DT, ANN, RF, LR, XGBoost, and kNN) were used to determine the combinations that yield the highest diagnostic performance for breast cancer. The study was conducted on the Wisconsin dataset available on the Kaggle platform, and accuracy scores along with confusion matrices were computed for each feature selection–algorithm pairing. This approach not only identifies which combinations achieve superior performance but also highlights the contribution of effective feature selection to the performance of medical decision-support systems. In this way, the study underscores the importance of this critical step in developing accurate and efficient decision-support tools.

2. MATERIALS AND METHODS

2.1. Dataset

The study utilized the Breast Cancer Wisconsin (Diagnostic) Data Set, available on the Kaggle platform (UCI, 1995), which contains 569 samples. Each sample includes an identification number and a diagnosis label indicating whether the cell is benign or malignant. Apart from these two, the dataset consists of 30 quantitative features describing the morphology of cell nuclei. These features are derived from ten fundamental measurements—radius, texture, perimeter, area, smoothness, compactness, concavity, concave points, symmetry, and fractal dimension. For each measurement, three types of values are recorded: the mean, the standard error, and the worst (the average of the three largest observed values).

2.2. Feature Selection Methods

In ML, feature selection plays a critical role in enhancing model performance and eliminating irrelevant variables. IG quantifies the impact of a feature on the target variable based on entropy and conditional entropy, where $H(Y)$ represents the entropy of the target variable and $H(Y|X)$

denotes the conditional entropy of Y given X (Hall, 1999; Novakovic et al., 2011). The Chi-Square test, particularly for categorical data, evaluates whether a feature has a statistically significant association with the target class; features lacking significant association can be removed from the dataset (Ünver et al., 2021). The Relief algorithm assesses how well each feature discriminates between classes by leveraging the similarity among instances (Kira & Rendell, 1992). ANOVA-F compares the mean values of features across class labels using one-way analysis of variance, with the F-statistic indicating statistically significant differences between classes (Fisher, 1918; 1925). L1 Regularization introduces a penalty term based on the sum of absolute values of coefficients in regression models, effectively shrinking some coefficients to zero and thereby removing redundant features (Tibshirani, 1996). The Pearson correlation coefficient (r) measures the linear relationship between two variables, where –1 or +1 indicates a perfect negative or positive correlation, and 0 indicates no correlation (Schober et al., 2018).

2.3. Machine Learning

Among the classification algorithms used in this study, ANNs are models inspired by the human brain, composed of densely interconnected nodes that learn by analyzing training data (Rumelhart et al., 1986). LR is a supervised method commonly applied in binary classification problems, providing probability estimates between 0 and 1 using the sigmoid function (Cox, 1958). The RF method generates ensemble models composed of multiple decision trees and determines the class based on a majority voting mechanism (Breiman, 2001). SVMs aim to find the optimal hyperplane that separates data into two classes; for non-linearly separable data, kernel techniques are applied (Cortes & Vapnik, 1995). DTs classify data based on simple decision rules derived from feature values, organized hierarchically in a tree structure (Quinlan, 1986). The kNN method estimates the class or value of a given data point by considering the classes or values of its k closest neighbors (Cover & Hart, 1967). NB is a probabilistic classifier that assumes feature independence and predicts the most likely class using Bayes' theorem (Mitchell, 1997). Finally, XGBoost employs a gradient boosting approach to create fast, flexible, and scalable ensemble models, achieving high performance especially on large datasets (Chen & Guestrin, 2016).

3. EXPERIMENTAL STUDY

Initially, data preprocessing steps were performed in the study. Outliers were detected in certain features of the dataset, and since these values could potentially negatively impact model performance, they were adjusted using threshold-based capping rather than being removed. For each variable, lower and upper threshold values were defined, and values falling outside these limits were replaced accordingly. This approach prevented data loss while preserving the overall distribution of the dataset. Additionally, since the features had different value ranges, which could lead to imbalanced results during the training of some algorithms, all data were normalized to the range of 0–1 using the Min-Max scaling method. This normalization particularly improved the performance of distance-based algorithms and enhanced the overall accuracy of the models.

Following data preprocessing, various feature selection methods (IG, Chi-Square, Anova F, Relief, L1 Regularization, and Pearson Correlation Coefficient) were applied to support breast cancer diagnosis. These feature selection methods were combined with ML algorithms including NB, SVM, DT, ANN, RF, LR, XGBoost, and kNN. The experimental results clearly demonstrate the impact of feature selection on the accuracy and classification performance of the ML algorithms. The accuracy values obtained by the algorithms with different feature selection methods are presented in Table 1.

Table 1. Performance Metrics of Algorithms According to Feature Selection Methods

	IG	Chi-Square	Anova F	Relief	L1	Correlation
ANN	98.25(10)	98.25(10)	**99.12(10)**	98.25(7)	---	99.12(25)
LR	98.25(21)	98.25(18)	98.25(18)	98.25(21)	**98.25(12)**	98.25(25)
RF	96.49(20)	**96.49(3)**	---	96.49(21)	---	96.49(25)
SVM	98.25(21)	**98.25(16)**	98.25(20)	98.25(21)	---	97.37(25)
NB	98.25(12)	**98.25(11)**	98.25(12)	98.25(15)	---	97.37(25)
DT	**95.61(25)**	93.86(15)	93.86(11)	93.86(20)	---	92.11(25)
KNN	98.25(11)	**98.25(7)**	98.25(11)	98.25(10)	---	96.49(25)
XGBoost	96.49(7)	**96.49(5)**	96.49(9)	96.49(9)	---	95.61(25)

Table 1 presents the accuracy values and the number of selected features for each classification algorithm–feature selection method combination. Bold values mark the maximum accuracy for each algorithm. We prioritize the model that reaches this highest accuracy using the least number of features, emphasizing efficiency and simplicity. "---" denotes non-applicable scenarios. Overall, ANN achieved the highest performance, reaching 99.12% accuracy with the Anova F filter, while correlation-based methods also yielded high performance, albeit less pronounced than Anova F. LR demonstrated consistent performance around 98.25% across all feature selection methods, with particularly compatible results observed using L1 Regularization. RF attained its highest accuracy of 96.49% with the Chi-Square method; the minimal variation across different feature selection methods highlights the effectiveness of RF's intrinsic feature importance mechanism. SVM and NB both exhibited stable performance, achieving 98.25% accuracy with Chi-Square and correlation-based methods, reflecting SVM's margin-maximization principle and NB's independence assumption as foundations for their robust performance. DT performed best with Information Gain (95.61%), emphasizing the importance of aligning splitting criteria with feature selection. The kNN algorithm reached 98.25% accuracy with Chi-Square and maintained similar stability across other methods. XGBoost achieved 96.49% accuracy with five features selected by Chi-Square and demonstrated stable performance across alternative methods. Feature selection strategies were observed to modulate the accuracy and generalization capabilities of the classifiers. Certain algorithms exhibited optimal performance and enhanced operational stability contingent upon their deployment with judiciously selected feature subsets.

4. CONCLUSION

In this study, commonly used ML algorithms for breast cancer diagnosis were compared, and their performance was evaluated in terms of accuracy. The application of the Anova-F feature selection method enabled the ANN model to achieve the highest performance, reaching 99.12% accuracy using only ten features. The findings demonstrate that robust feature selection methods, particularly when combined with deep-structured models, enhance predictive performance, while also highlighting the impact of data preprocessing steps on overall model accuracy.

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COMPARATIVE ANALYSIS OF TRADITIONAL MACHINE LEARNING AND DEEP LEARNING MODELS IN LANGUAGE IDENTIFICATION PROBLEMS

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ABSTRACT

The rapid increase in multilingual content in the digital environment has made it essential to correctly identify texts and assign appropriate language tags. This directly affects the accuracy of text classification, automatic translation, sentiment analysis, search engine optimization, and security systems. This study compares the performance of traditional machine learning (ML) methods with deep learning (DL)-based models for the language detection problem. The study evaluated Logistic Regression (LR), Naive Bayes (NB), Random Forest (RF), and Support Vector Machine (SVM) methods, as well as Long Short-Term Memory (LSTM), Gated Recurrent Unit (GRU), and DistilBERT models. These models were trained on the same dataset and tested comparatively. According to the research results, the DistilBERT model demonstrated the highest success with 99.22% accuracy and a 99.23% F1-macro score. This difference was found to be statistically significant. The results demonstrate that Transformer architecture has high potential for learning multilingual representations and enhancing inter-class discrimination. However, considering training time, hardware requirements, and sustainability metrics (e.g., energy consumption, model size, and re-trainability), the NB model was found to offer a more balanced solution in terms of application and automation processes. The results show that accuracy rates alone are not decisive in the field of language detection. Efficiency, resource utilization, and model scalability are also important factors to consider. Therefore, this study provides a guiding framework for model selection in multilingual text processing projects from both theoretical and practical perspectives.

Introduction

Language detection is one of the fundamental components of Natural Language Processing (NLP). The rapid increase in multilingual digital content has made this topic even more important in recent years. Today, content produced in online environments is often written in multiple languages. This makes it important for texts to be labelled correctly.

The success of many systems, such as social media analytics, search engines, machine translation, and cybersecurity applications, depends on the ability to correctly identify the language of the text. Language detection is not merely a classification problem. It is also a complex process that requires distinguishing the statistical, morphological, and contextual features of the language (Song et al., 2024).

In some languages, superficial statistical methods may suffice. For example, n-gram-based statistical features generally yield successful results in languages that use the Latin alphabet, such as English, French, and Italian. However, languages with different writing systems, such as Arabic, Hindi, Malayalam, or Tamil, require deep contextual learning models (Ilic et al., 2022). Therefore, achieving high accuracy with a single method is often not possible. This necessitates analyzing the strengths and weaknesses of different modelling approaches.

Early research on language detection typically began with statistical methods. In these studies, character sequences and probabilistic models were used to statistically examine the differences between languages. This period represents a stage in which n-gram and probability-based approaches, which form the basis of language recognition, were prevalent. Over time, with the increase in data volume and the advancement of computational power, statistical models began to be replaced by machine learning (ML) and deep learning (DL)-based methods. This transformation has led to significant advances in language representation. Transformer-based architecture has had a groundbreaking impact in this field. However, some studies show that classical methods can still yield effective results in certain situations. For example, Lui et al. (2012) demonstrated that the Naive Bayes (NB) method performs strongly. Conneau et al. (2020) demonstrated that multilingual representations can be learned at scale in an unsupervised manner and proposed the XLM-R model. This work has greatly improved the accuracy and generalization power of contextual representations in multilingual texts. Luo et al. (2021) improved representation quality by re-examining the language encoding processes of Transformer models using the "Cross-lingual Language Projection (XLP)" approach. Such studies have demonstrated that Transformer-based models are effective in multilingual language detection tasks. On the other hand, Recurrent Neural Network (RNN)-based models have not been completely abandoned. Long Short-Term Memory (LSTM) and Gated Recurrent Unit (GRU) based networks are still considered valid alternatives, especially for short or low-resource languages. For example, in their study, Aysa et al. (2023) used the SE-Res2Net-CBAM-BiLSTM architecture to enable the learning of audio-based contexts in language detection. Kocmi & Bojar (2017) developed a Bidirectional Recurrent Neural Network (BRNN)-based method for language identification in their work. The study also showed that while some applications perform language identification using the NB method, the proposed model is more successful in analyzing complex language structures. Bharathi Mohan et al. (2023) presented a comprehensive evaluation of various Transformer architectures for the language detection task in their work.

In the current study, LSTM and GRU-based RNN models, the Transformer-based DISTILBERT model, FastText and LangDetect external services, and the classical methods NB, Logistic Regression (LR), Random Forest (RF) and Support Vector Machine (SVM) were compared on the same dataset. The results obtained were presented to the user. The aim of the

study is to compare the speech recognition performance of different ML, DL, and external service-based models, determine the most suitable model, and integrate it into a real-time system. The study systematically evaluated not only classical ML algorithms but also modern DL and Transformer methods. Thus, the advantages, limitations, and practical applicability of different methods were examined comparatively.

Methodology

In this study, NB, LR, RF, and SVM classical methods were used. The aim of these methods is to train classifiers based on features extracted using TD-IDF. K-fold cross-validation was used in model training. This method is based on dividing the model into different sections and using each part for testing in different rounds (Song et al., 2024). In addition, hyperparameter optimization was performed. Grid Search was applied for LR and NB. The Random Search method was applied for RF and SVM.

Alongside traditional methods, LSTM, GRU, and DistilBERT models were also applied. In DL approaches, inputs are typically provided as embedding representations. Model layers are processed using, for example, LSTM/GRU or transformer blocks. Transformer models have the advantage of capturing contextual language representations. For example, XLM-E has been shown to provide better cross-language transfer in multilingual pre-training (Chi et al., 2022). For transformer models, hyperparameters such as learning rate, batch size, and number of layers were adjusted during training. Early stopping and model checkpoint techniques were also used.

In the study, NB, LR, RF, LinearSVC, and SVM-RBF models were trained using the Scikit-learn library. LSTM and GRU models were trained based on PyTorch, with embedding size 128 and dropout rate 0.2 parameters. The DistilBERT model was trained within the Hugging Face Transformers framework using a fine-tuning method based on "distilbert-base-multilingual-cased".

Comparison Criteria and Evaluation Methods

The performance of the models was evaluated using accuracy, precision, recall, and F1-score metrics. Additionally, the confusion matrix was used to examine which languages the models confused with each other. During the experiments, data splitting (training/validation/test sets) was carefully performed to assess the model's generalization ability.

Class-based reports were generated for all models, metrics were recorded in JSON format, and visualization (ROC, Loss, Accuracy) analyses were performed. The same test set was used for externally serviced models. FastText, LangDetect, and Gemini results were additionally evaluated for verification purposes.

Dataset Details

The dataset used in the study is the *Language Detection* Dataset on the Kaggle platform (Basil, 2023). The dataset contains 10,267 unique short sentences written in different languages. Each row contains a text and, correspondingly, the language tag in which the sentence is written. The dataset provides a broad testing ground for the language detection problem.

- Detection and removal of missing or corrupted records.
- During the data pre-processing stage, spaces, special characters, and line breaks in the texts were cleaned. Each example was converted into a "text–language" pair.
- Lowercase conversion
- Tokenization: both word-based and character-based approaches
- Feature extraction: TF-IDF-based representations

First, the "data summary information" (Figure 1) and "language distribution graph" (Figure 2) revealed by the data set analysis are shown below.

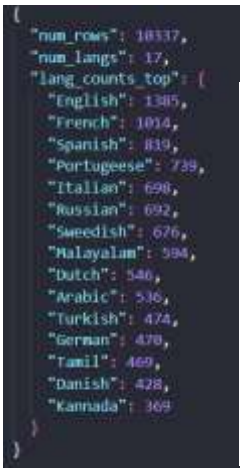

Figure 1. Data Summary

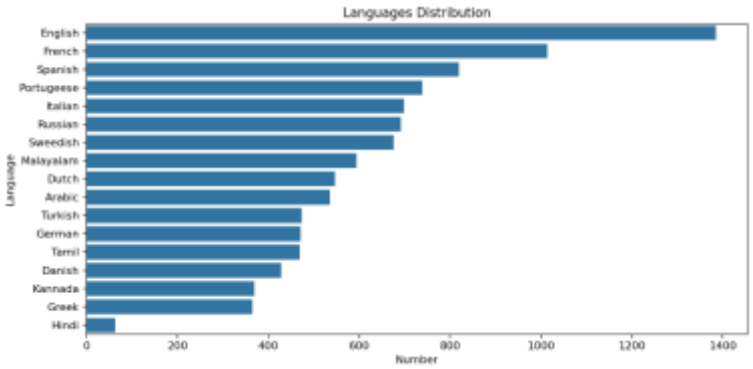

Figure 2. Language Distribution

Application

An application was implemented using the most successful model identified. During this process, a simple interface application running in a web environment was designed using the "streamlit" library. In the simple interface developed, the predicted language and probabilities are displayed instantly when the user enters text. These screenshots (Figures 3, 4) clearly demonstrate the decision speed and ease of use.

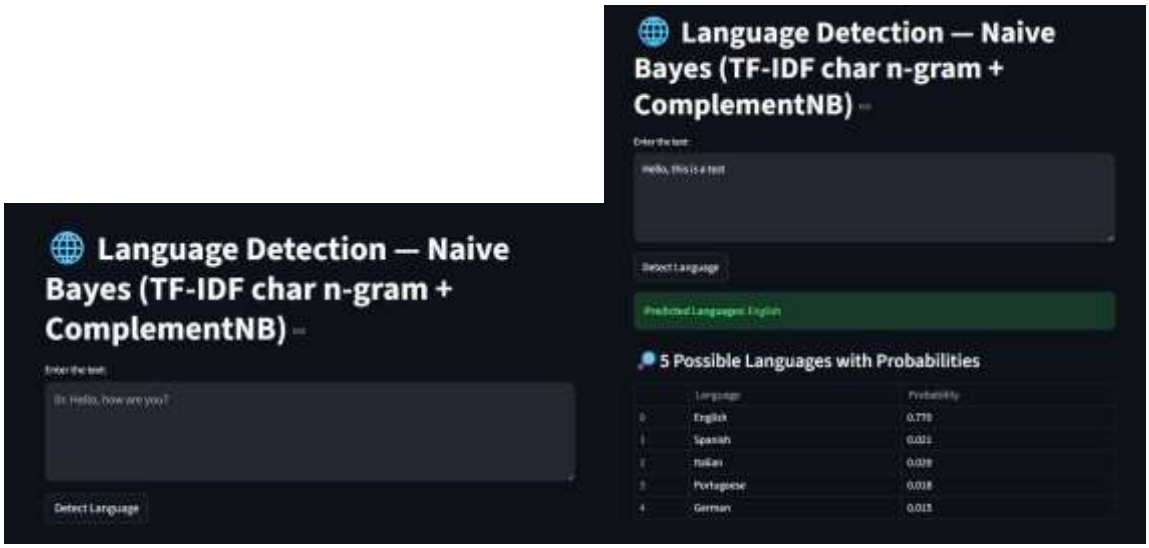

Figure 3. Application Screen Visualization

Figure 4. Application Screen Visualization

Results

Within the scope of the project, investigations were conducted under three main headings for language detection.

Traditional Methods

In this section, model training was performed using the LR, NB, RF, SVM, and LinearSVC algorithms, which is a type of SVM application. The results and confusion matrices showing these results are collectively presented in Figure 5 below.

Logistic Regression (LR)

LR is a statistical-based method of classification that creates linear decision boundaries in text data (Jurafsky & Martin, 2025). In this study, it was optimized using Grid Search and achieved an accuracy rate of approximately 99.08%. This method yielded precision and recall values above 99% for almost all languages. Predictions are nearly flawless, particularly in the English, French, Spanish, and German classes. A very low rate of confusion was observed in phonetically similar languages such as Danish and Dutch; however, this error rate is low enough not to affect the overall success of the model. LR stands out as a strong baseline model with low computational cost.

Naive Bayes (NB)

The NB model exhibits a probabilistic approach based on word distribution and is known for its speed advantage, particularly in text classification tasks (Raschka, 2014). In this study, this method was optimized using Grid Search, achieving an accuracy rate of approximately 98.98%. Performance was very high in classes with distinct word structures, such as Japanese, Arabic, and Greek. However, minor misclassifications were observed among Scandinavian and Western European languages. Despite this, the model's overall consistency is high, and it offers a viable solution for systems requiring fast predictions due to its low resource requirements.

Random Forest (RF)

RF works with an ensemble structure created by combining multiple decision trees (Xin, 2018). In this study, the accuracy value after training the RF model was calculated to be approximately 97.82%.

Although the model showed high success in languages with distinct character-based separations, an overfitting tendency was observed in languages with limited data. This situation led to recall values being lower than precision in some classes. It was the slowest model among the classical methods, but it can be considered a reference due to its stable discrimination power.

Support Vector Machine (SVM)

SVM draws an optimal decision boundary between classes by creating margin-maximizing separation surfaces.

In this study, the RBF kernel was chosen as the SVM model. This choice enabled the model to learn non-linear patterns. As a result, the complex boundaries between language features were separated more effectively.

After all these optimization processes, the model's accuracy rate was measured at approximately 98.06%.

The model has shown high success, particularly in languages with structurally different alphabets (Japanese, Arabic, Hindi). However, a small amount of confusion was observed in closely related language pairs such as German–Dutch or French–Italian. Although the computational cost is higher than LR, it provided a flexible decision surface thanks to the RBF kernel.

LinearSVC

LinearSVC is an optimized SVM variant capable of fast classification using linear hyperplanes in high-dimensional text spaces (Soni, 2023). In this study, it was optimized using Grid Search and achieved 99.32% accuracy, yielding the best result among all traditional methods. Specifically, both precision and recall values were very close to 100% in the English, French, Spanish, and Greek classes. It is the model with the lowest confusion rate and can be considered the strongest traditional approach in the report in terms of accuracy-speed balance.

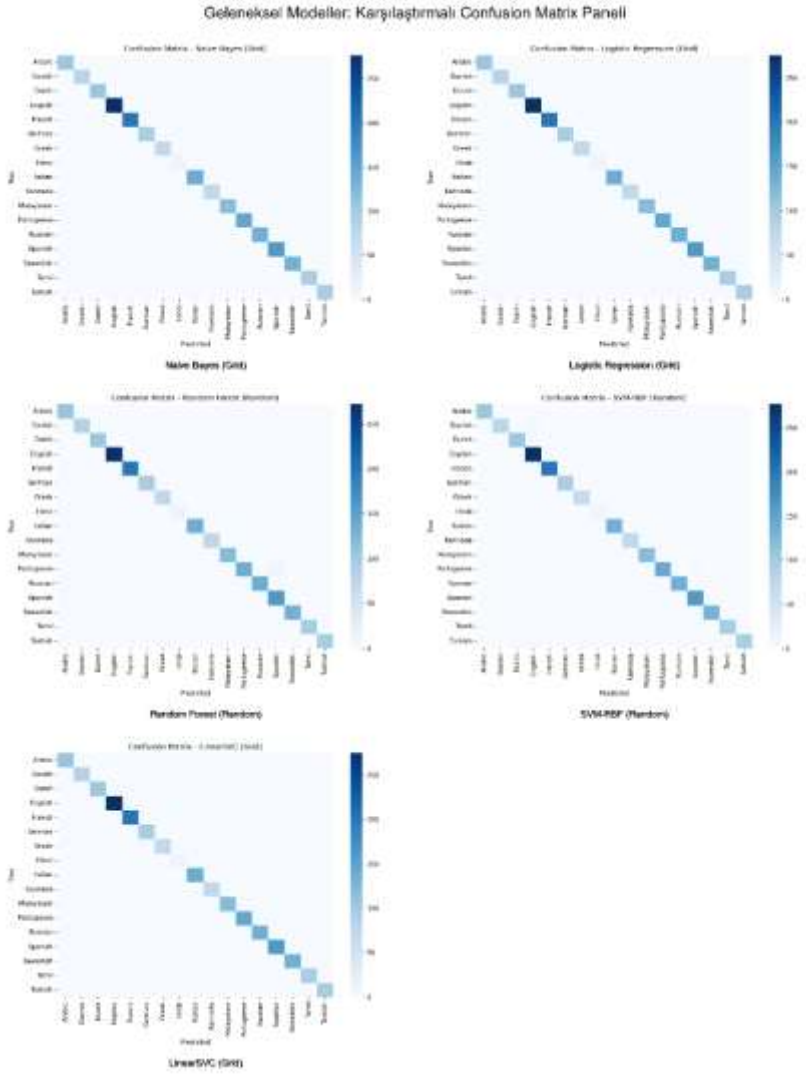

Figure 5 Confusion Matrices of Traditional Methods

The comparative performance of traditional ML methods is clearly shown in Figure 5. All models made accurate predictions with high accuracy across classes, and cross-errors were quite limited. NB and LR showed stable performance, especially in balanced classes. The RF and SVM-RBF models maintained their overall accuracy level despite showing partial deviations in some languages (e.g., short texts). Overall, the stability of all models demonstrates that statistical approaches are still a strong alternative for language detection.

Current Methods

In this section, training was performed using the DISTILBERT model, which is an LSTM, GRU, and Transformer-based model. Before model-based analyses, the languages were labelled. This is an important step for these methods to work. The results after labelling are shown in Figure 6.

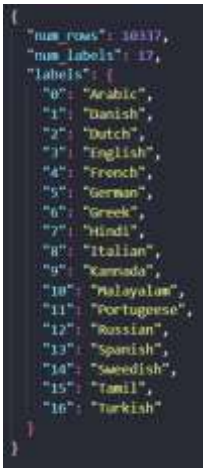

Figure 6. Language Labelling for Current Methods

The results of these training sessions and the summary of the result graphs are shown below (Figure 7).

Long Short-Term Memory (LSTM)

The LSTM model was trained using early stopping and achieved 95.35% accuracy and a 95.57% F1-macro score. The average AUC was reported as 0.9986, demonstrating that it successfully learned the classification boundaries. LSTM performed particularly well in Latin-based languages but showed lower segmentation performance compared to the Transformer model when applied to languages with structurally different character sequences (such as Japanese, Hindi, and Greek). Nevertheless, the model's ability to produce stable and consistent results demonstrates that it is an alternative that can operate at a lower computational cost.

Gated Recurrent Unit (GRU)

The GRU model was optimized using early stopping, similar to LSTM, and achieved 95.06% accuracy and a macro-F1 score of 94.88%. In the class-based AUC analysis, the macro-AUC value was measured as 0.9986, showing that it has almost the same overall discrimination power as LSTM. Although the training time was shorter than that of LSTM, slight decreases in recall values were observed in some classes with low sample counts. This indicates that GRU provides a speed advantage but is not as strong as LSTM in terms of memory control.

DISTILBERT Model

The DistilBERT model demonstrated the highest performance in the study, achieving 99.22% accuracy and a 99.23% F1-macro score. When examining the AUC values, values of 0.9995

and above were obtained for each class, and the macro-AUC was reported as ≈ 1.000. This result shows that the model not only classifies correctly but also establishes the decision boundary between classes extremely clearly.

Thanks to its Transformer-based structure, DistilBERT represents texts not only based on word frequency but also by considering contextual relationships, offering a meaning modelling capacity beyond traditional statistical methods. This becomes particularly evident when applied to morphologically rich languages or languages with different alphabets (e.g., Arabic, Greek, Japanese), where the model achieved nearly flawless classification.

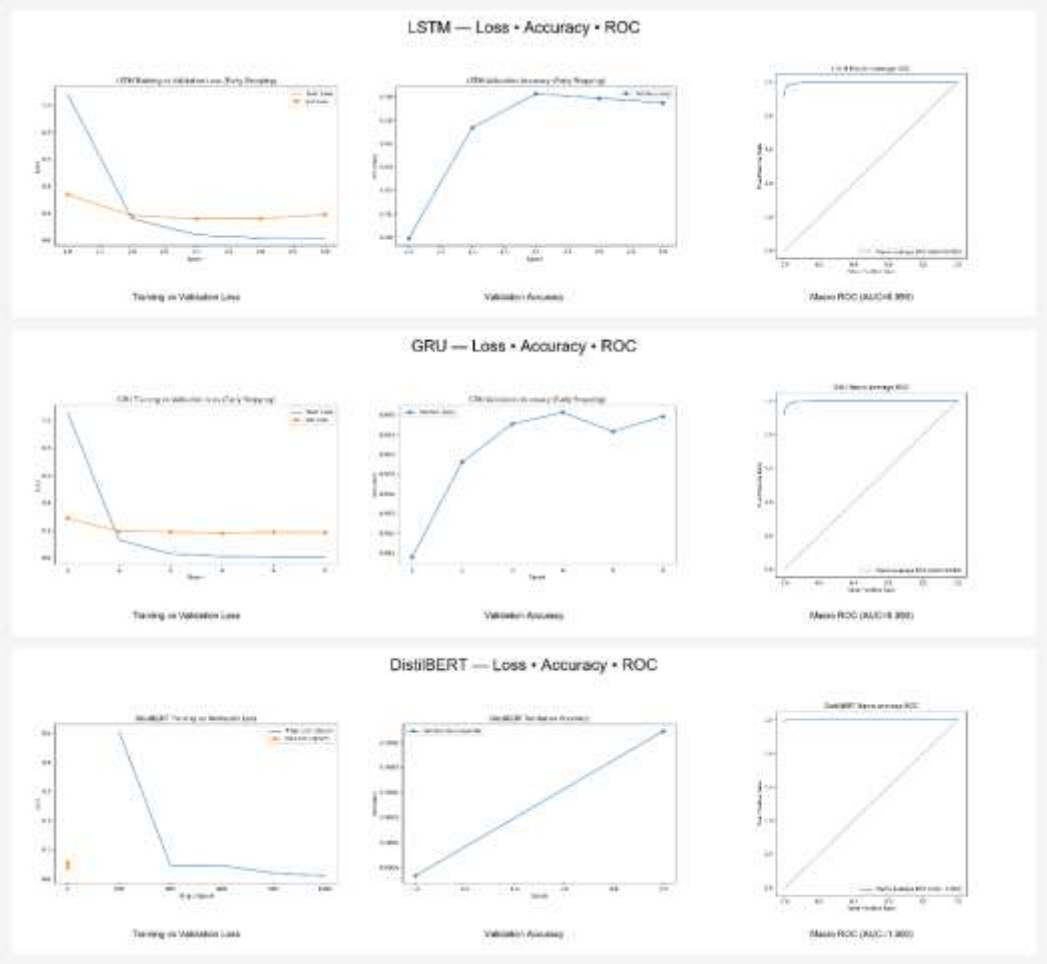

Figure 7 Graphs for Current Methods

When examining the graphs in Figure 7, all three models exhibit high accuracy and discrimination power. The LSTM and GRU models achieved balanced learning with the early stopping technique, reaching around 95% accuracy and F1 scores. The AUC scores of both models are also at 0.998 level, indicating strong overall performance. In contrast, the Transformer-based DistilBERT model showed the highest success with accuracy and F1 scores above 99%. This result demonstrates that DistilBERT, thanks to its ability to learn contextual representations, performs superior classification on multilingual datasets compared to LSTM and GRU models.

External Service Models

FastText

FastText tends to lag behind Transformer-based models when the dataset contains spelling variations, mixed/very short texts, or non-Latin alphabets. However, its training and inference speed is very good, making it a reasonable choice for rapid prototyping or resource-constrained systems. The model's results on the test set were recorded as 94.19% accuracy, 95.60% macro-precision, 94.28% macro-recall, and 94.43% macro-F1.

LangDetect

In this model, the macro-F1 drop is particularly noticeable in very short and code-mixed sentences. The limitations of rule-based/statistical approaches become apparent here. Although strong in some languages, class imbalance and short segments negatively affect performance. In terms of performance, it appears to be the weakest among all models and metrics compared. The results achieved by the model on the test data were measured as 82.98% accuracy, 74.16% macro-precision, 72.32% macro-recall, and 73.18% macro-F1.

Comparative Analysis

The test performance of all models is summarized in a single graph, along with the accuracy, precision, recall, and F1-score metrics (Figure 8).

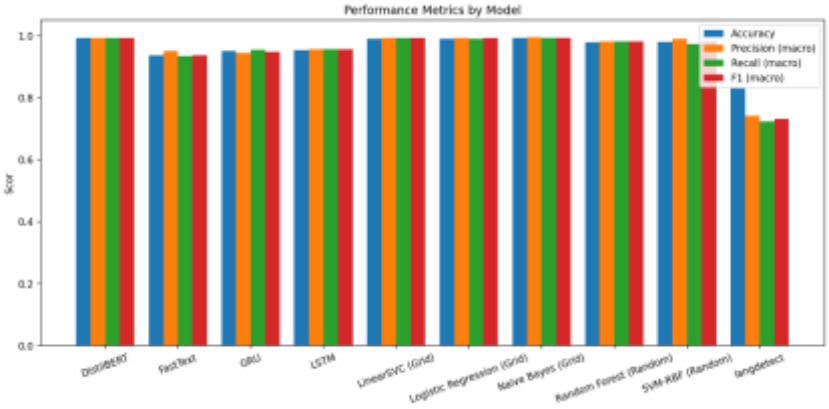

Figure 8. Common Graph of All Metrics

Additionally, sequential bar charts for each metric show the differences between models more clearly. Figures 9, 10, 11, and 12 below are these bar charts.

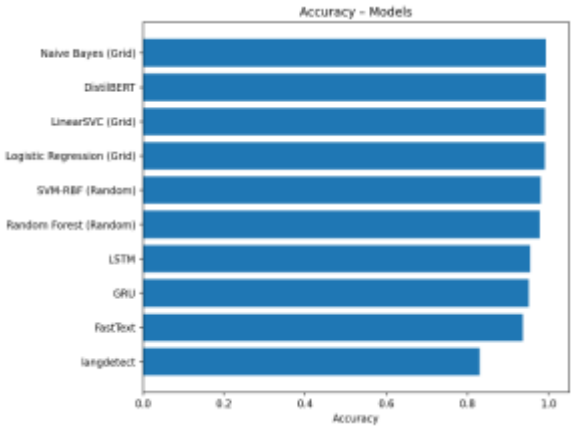

Figure 9 Accuracy

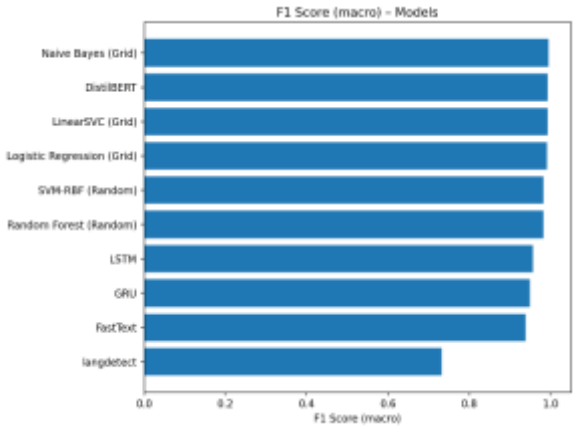

Figure 10 F1-Score

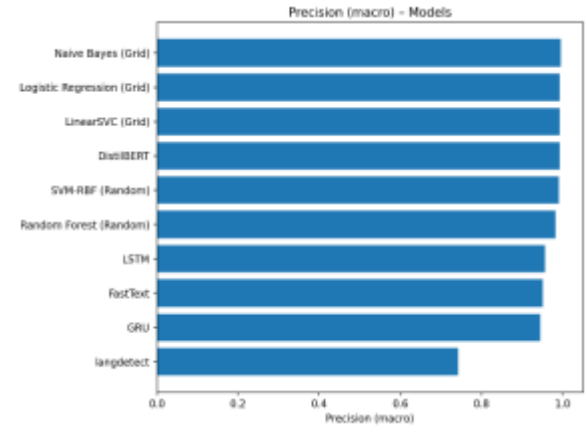

Figure 11 Precision

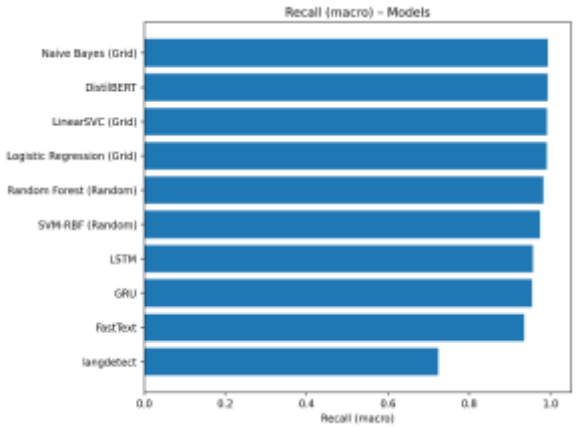

Figure 12 Recall

Accuracy and Consistency: DistilBERT demonstrated the highest overall performance on the test set with >99% accuracy and macro-F1 and clearly distinguished between classes with macro-AUC ≈ 1.000. LSTM/GRU produced high performance with relatively low resources, while NB stood out among classical methods thanks to character n-gram representation.

In terms of resource/cost balance, NB offers a practical solution with low latency and a small footprint, as latency, memory consumption, and sustainability are important in production scenarios. The system determined the optimal value for each metric for the application. Subsequently, the system was asked to recommend a model, considering the F1-Accuracy-Inference time parameters. As shown in Figure 13, the system selected NB as the "application model".

```
Suggested Model (For App)
Model: Naive Bayes (Grid)
F1(macro): 0.9940
Accuracy : 0.9932
Infer (sn/örnek): 0.000256
Explanation:
- The highest F1-macro value was measured in model Naive Bayes (Grid).
- Accuracy Score: 0.993.
- Infer Time is 0.000256 so it is usable in Real Time Usage.
- For that reasons, this model is recommended for application deployment.
```

Figure 13. Model Recommendation by the System Based on Analysis Results

Conclusion

In this study, both traditional statistical methods and modern DL and Transformer-based models were comparatively evaluated for the language detection task. The results revealed that the strengths of different approaches vary depending on the application context.

According to the experimental findings, the DistilBERT model demonstrated the highest performance in terms of accuracy. The model's accuracy rate of 99.22% and F1-macro score of 99.23% clearly demonstrate the Transformer architecture's power of contextual representation in multilingual texts. The LSTM and GRU models achieved high but more limited success after DistilBERT, thanks to their proficiency in capturing sequential data structures. The accuracy of these models in the range of 81–83% shows that RNN-based networks are still effective in understanding linguistic patterns.

The FastText model offered a practical solution, particularly for resource-constrained systems, due to its short training and inference times. While it performs strongly in languages using the

Latin alphabet, its success rate is relatively lower in mixed writing systems (e.g., Hindi and Arabic). LangDetect, relying on simple statistical rules, offers a limited accuracy level (62.34%) for short, incorrect, or multilingual texts.

Considering the accuracy, training time, processing cost, and ease of implementation of all models, the NB model provided the most suitable results in terms of overall balance. The model demonstrated both fast and reliable performance with a 96.12% accuracy rate and low processing cost. Therefore, the NB model was chosen as the core structure in the developed language detection automation system. However, the DistilBERT model is recommended as a second option in research environments where the highest level of accuracy is required.

In conclusion, this study has demonstrated that model selection in the field of language detection should be based not only on accuracy values but also on practical criteria such as system resources, speed, scalability, and sustainability. Future work could include adding low-resource languages, investigating model adaptations on code-mixed datasets, and creating hybrid systems with large language models such as Gemini. These developments would enable the creation of more inclusive, faster, and more reliable language detection systems for both academic and industrial applications.

Declarations

During the preparation of this work, the authors used OpenAI ChatGPT to improve the readability and language of the work. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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FAZ DEĞİŞİM MALZEMELİ (FDM) ÇİFT BORULU ENERJİ DEPOLAMADA İÇ BORU GEOMETRİSİNİN ENERJİ DEPOLAMA KARAKTERİSTİĞİNE ETKİSİNİN SAYISAL OLARAK İNCELENMESİ

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ÖZET

Faz değiştiren malzeme (FDM) kullanılan çift borulu ısıl enerji depolama sistemlerinde iç boru geometrisinin enerji depolama karakteristiği üzerindeki etkisi sayısal olarak araştırılmıştır. Analizler, Hesaplamalı Akışkanlar Dinamiği (HAD) yaklaşımıyla ANSYS Fluent yazılımı kullanılarak üç boyutlu (3B) ve zamana bağlı olarak gerçekleştirilmiştir. Sayısal modelin oluşturulmasında, erimiş nitrat tuzunun termofiziksel özellikleri referans alınmış ve faz değiştiren malzemenin ısı depolama performansı entalpi-gözeneklilik yöntemi kullanılarak değerlendirilmiştir. Modelleme aşamasında enerji, momentum ve süreklilik denklemleri çözümlenmiş, katı-sıvı faz geçişi sırasında gerçekleşen ısı transferi ve akış davranışı detaylı biçimde analiz edilmiştir. Çalışma kapsamında iç boru geometrisi, alanı sabit kalacak şekilde dairesel, kare ve üçgensel olmak üzere üç farklı formda modellenmiştir. Bu yaklaşım, geometrik farkların yalnızca akış karakteristiği ve ısı transfer mekanizmaları üzerindeki etkisini değerlendirmeyi mümkün kılmıştır. Her bir model için ağ (mesh) yapısı kalite kriterlerine göre optimize edilmiş, simülasyonlar 100, 200 ve 300 saniyelik iterasyon sürelerinde yürütülmüştür. Her bir zaman adımında faz değiştiren malzemenin erime oranı, sıcaklık dağılımı, enerji depolama kapasitesi ve ortalama ısıl verimi hesaplanmıştır. Elde edilen sonuçlar, üçgen kesitli iç boru geometrisinde ısıl verimin diğer geometrilere kıyasla daha yüksek olduğunu göstermiştir. Üçgen kesitli yapı, akış alanında daha yoğun türbülans oluşturduğu için ısı transfer katsayısını artırmış ve faz değişim süresini kısaltmıştır. Dairesel ve kare kesitli geometrilerde ise sıcaklık dağılımı daha düzensiz bir profil göstermiştir. Sonuç olarak, iç boru geometrisinin seçimi, faz değiştiren malzemeli enerji depolama sistemlerinde ısıl performansın artırılması, enerji yoğunluğunun yükseltilmesi ve tasarım optimizasyonu açısından kritik bir parametre olarak belirlenmiştir.

Anahtar Kelimeler: Faz değiştiren malzemeler, Hesaplamalı akışkanlar dinamiği (CFD), Isıl Analiz

NUMERICAL INVESTIGATION OF THE EFFECT OF INSIDE PIPE GEOMETRY ON ENERGY STORAGE CHARACTERISTICS IN DOUBLE PIPE ENERGY STORAGE WITH PHASE CHANGE MATERIAL (PCM)

ABSTRACT

In this study, the effect of the inner tube geometry on the thermal energy storage characteristics of a double-pipe energy storage system using phase change material (PCM) was numerically investigated. The analyses were performed in three dimensions (3D) and in a transient manner using the Computational Fluid Dynamics (CFD) approach within the ANSYS Fluent software. The numerical model was developed based on the thermophysical properties of molten nitrate salt, and the thermal performance of the PCM was evaluated using the enthalpy–porosity method. During the modeling stage, the energy, momentum, and continuity equations were solved, and the heat transfer and flow behavior occurring during the solid–liquid phase transition were analyzed in detail. Within the scope of this study, the inner tube geometry was modeled in three different forms—circular, square, and triangular—while keeping the cross-sectional area constant. This approach allowed for isolating the geometric effects on the flow characteristics and heat transfer mechanisms without introducing area-based discrepancies. The mesh structure for each configuration was optimized according to quality criteria, and the simulations were carried out for iteration times of 100, 200, and 300 seconds. At each time step, the melting rate, temperature distribution, stored thermal energy, and overall thermal efficiency of the PCM were computed and compared. The results revealed that the triangular inner tube geometry exhibited higher thermal efficiency compared to the circular and square geometries. The triangular configuration generated a stronger turbulent flow field, thereby enhancing the heat transfer coefficient and reducing the total melting duration. In contrast, the circular and square geometries produced less uniform temperature profiles within the PCM domain. Consequently, the selection of inner tube geometry has been identified as a critical design parameter for improving thermal performance, increasing energy density, and optimizing the design of PCM-based thermal energy storage systems.

Keywords : Phase change materials, Computational fluid dynamic, Heat transfer

1. GİRİŞ

Artan karbon salınımıyla iklim değişikliği meydana gelmektedir. Bu duruma artan nüfusla birlikte enerji tüketimi sonucu ortaya çıkan egzoz gazları sebep olmaktadır. Dünyamızı korumamız için başta karbon salınımını azaltmayı amaçlayıp çevreye duyarlı teknolojiler geliştirmeye devam etmeliyiz. Bu amaçla özellikle güneş enerjisinin faydalı bir şekilde depolanması başta olmak üzere enerjiyi depolama önem arz etmektedir.

Enerji; ısıl, kinetik, mekanik, potansiyel, nükleer, kimyasal vb. birçok biçimde bulunabilmektedir. Bütün biçimlerin toplamına da toplam enerji denilmektedir. Bir sistemin iç enerjisinin moleküllerinin kinetik enerjisi yani duyulur ısı olarak tanımlanmaktadır.

Güneş enerjisini depolamanın en çok kullanılan enerji depolama şekli duyulur ısıdır. Son yıllarda gizli ısı depolama üzerine faz değiştiren malzemelerin gelişmesiyle gizli ısıda alternatif yöntem olmuştur. Duyulur ısı yani geleneksel yöntemle enerji depolama yalıtım, sızıntı vb. nedenlerden dolayı maliyet dezavantajlarına sahiptir. Gizli ısı depolama ile küçük boyutlarda daha fazla güneş enerji depolanarak kullanılması güneş enerjisinden sıcak su elde edilmesi en uygun yöntemi olmaktadır. (Iten ve Liu 2014).

Faz değişimine bağlı olarak soğumak ve ısınmak için enerji alan/veren maddelere faz değiştiren malzemeler (FDM) denir. Isı transferi katı-sıvı-gaz arasında olmaktadır fakat FDM' lerde genel olarak katı-sıvı arasında gerçekleşmektedir. Katı fazdan sıvı faza geçerken alınan/verilen gizli ısı miktarı duyulur ısı miktarından fazla olmaktadır. Örnek olarak suyun katı fazı 0 °C (buz) erime gizli ısısı h_if 333,7 kJ/kg iken suyun sıvı fazını 10 °C arttırmak için 4,22 kJ/kg enerji verilmesi gerekmektedir. Bu sebepten dolayı buz/su çok değerli FDM malzemesi olarak kullanılmaktadır (Zhang 2001).

FDM' ler faz değişim sıcaklığında eriyerek ve katılaşarak duyulur ısı miktarına kıyasla büyük miktarda gizli enerji depolayabilir ve serbest bırakabilmektedir. Malzemenin iç yapısı değiştiğinde veya katı-sıvı faz değişimlerinde ısı yayılır/emilir bundan dolayı FDM' ler gizli ısı depolama malzemeleri olarak tanımlanır (Alnakeeb ve ark. 2021).

Faz değiştiren malzeme sınıfı olarak canlılardan elde edilen organik malzemeler, denizden veya maden yataklarından elde edilen doğal tuzlar kullanılmaktadır. Ayrıca değişik uygulamalarda katıdan katıya faz değiştiren malzemelerde bulunmaktadır.

FDM' lerin ticari olarak en çok kullanıldığı alanlar binaların soğutma ve ısıtma uygulamalarıdır. FDM' ler güneş enerjisini maksimum verimle olduğu zamanda depolayıp enerji talebinin en fazla olduğu zamanda kullanılmasını sağlamaktadır.

2. FAZ DEĞİŞTİREN MALZEMELERİN GENEL ÖZELLİKLERİ

Gizli ısı depolanması katı-sıvı-gaz aralarında değişik kombinasyonlarda olabilmektedir fakat FDM' ler katı-sıvı ve sıvı-katı fazlarında daha pratik olarak uygulanmaktadır. Sıvı-gaz geçişleri katı-sıvı arasındaki geçişten daha fazla gizli ısı barındırsa da malzemeleri gaz fazında depolamak zorlu olmaktadır (Duraković 2020).

Katı-sıvı FDM' ler ısı transferi başlangıcında duyulur ısı transferi gerçekleştirmektedir. Bu durumda ısı aldıkça sıcaklıkları yükselir daha sonra erime noktalarına ulaştıklarında tüm malzeme eriyene kadar sabit sıcaklıkta ısı almaktadırlar. Sıvı fazında ise etrafının sıcaklığı düştüğü zaman, FDM katılaşarak depolanan gizli enerjiyi serbest bırakmaktadır. -5 ile +190 °C arasında efektif olarak kullanılabilen FDM' ler bulunmaktadır. İnsanların rahat bir şekilde bulunabildiği 20-30°C sıcaklıkları arasında bazı FDM' ler çok etkili olarak kullanılabilmektedir (Duraković 2020).

Organik faz değiştiren malzemeler, insan, bitki ve hayvan organizmalarını etkeniyle ortaya çıkan malzemelerdir. Avantajları; aşırı soğutma yükü olmadan donma, kimyasal olarak kararlı olma, güvenli bir şekilde erime ve reaktif olmama, hacim değişikliği az olması, geniş sıcaklık aralığı diye sıralanabilir (Iten ve Liu 2014). Dezavantajları ise katı halde düşüş ısı iletimi. dondurma halinde yüksek ısı transferi miktarı ihtiyaç duyulmaktadır. Gizli ısı depolama kapasiteleri düşük olabilmektedir. Yanıcı olmalarıdır (Iten ve Liu 2014).

İnorganik faz değiştiren malzemelerin avantajları birim hacimde yüksek gizli ısı depolama, düşük maliyetle işletilebilme, yanıcı olmamasıdır. Dezavantajları ise faz değişimi esnasında uyumsuz erime ve faz ayrımını engellemek kolay olmamaktadır ve gizli ısı entalpisinde kayıp meydana gelebilmektedir. Metaller başta olmak üzere birçok malzeme için aşındırıcıdır. Bazı karışımların hacim değişimi yüksektir. Korozyona neden olabilir (Iten ve Liu 2014).

Parafin ve yağ asitleri uzun ömürlü ve stabil oldukları için en çok tercih edilen FDM' lerdir. Özellikle parafinler erime gizli ısısı yüksek, faz değiştirme esnasında stabil, çevreye ve sisteme duyarlı oldukları için yaygın olarak kullanılmaktadır. Parafinlerin dezavantajlarından biri de düşük ısıl iletkenlik katsayısına sahip olmasıdır. Bu amaçla FDM'ler üzerine çeşitli araştırmalar yapılarak iyileştirme yapılmaya çalışılmıştır (Iten ve Liu 2014).

3. MATERYAL METOT

Yapılan sayısal çalışmada iç geometrisi farklı çift borulu sistemde faz değişikliğini analiz etmek için entalpi-gözeneklilik metodu kullanılmıştır. Hesaplamada minimum hata için aşağıdaki varsayımlar yapılmıştır.

Erimiş FDM' de serbest konveksiyon laminar, sıkıştırılamaz ve geçici olarak kabul edilir.

Faz değişimi esnasında hacim değişimi göz ardı edildi.

Enerji denkleminde viskoz etkiler düşük sıvı hızları nedeniyle ihmal edilmiştir.

Dış borudan kaynaklanan ısı kaybı ihmal edilmiştir.

Momentum Denklemi

$$\frac{\partial \mathrm{v}}{\partial \mathrm{t}} + \vec{V}.\nabla\vec{V} = \frac{1}{\rho}\left(-\nabla \mathrm{P} + \mu\nabla^2\vec{V} + \rho\vec{g}\beta\left(T - T_{ref}\right)\right) + \vec{S} \quad (1)$$

Süreklilik denklemi

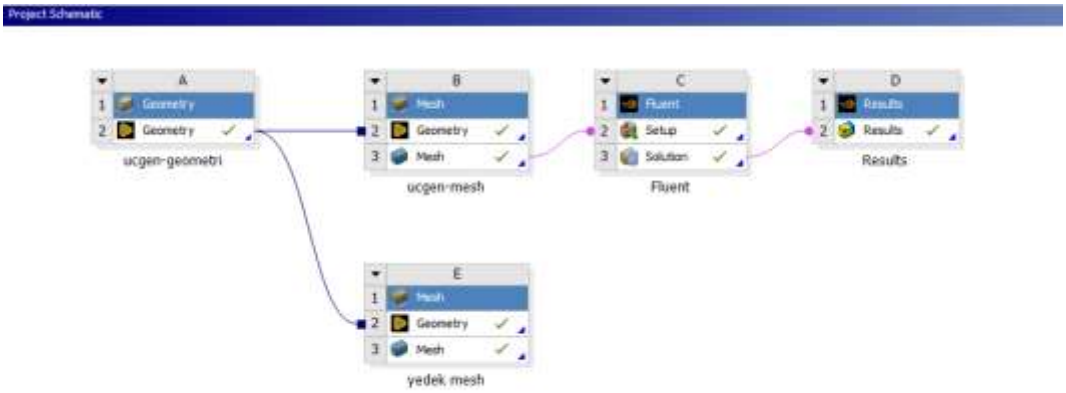
$$\Delta.\vec{V} = 0 \quad (2)$$

Enerji Denklemi

$$\frac{\partial \mathrm{h_{duy}}}{\partial \mathrm{t}} + \frac{\partial \mathrm{h}_{gizli}}{\partial \mathrm{t}} + \nabla.\left(\vec{V}\mathrm{h_{duy}}\right) = \nabla\left(\frac{k}{\rho \mathrm{cp}}\nabla \mathrm{h_{duy}}\right) \quad (3)$$

Türkiye'de genel olarak evlerde kullanılan sıcak su ve ısıtma ihtiyacı merkezi sistemlerde doğalgaz, kömür, linyit vb. yakıtlardan ve elektrik enerjisi kaynaklarından sağlanmaktadır. Isıtılan su yalıtımsız borular vasıtasıyla iletilirse mahal içinde de olsa kayıplar meydana

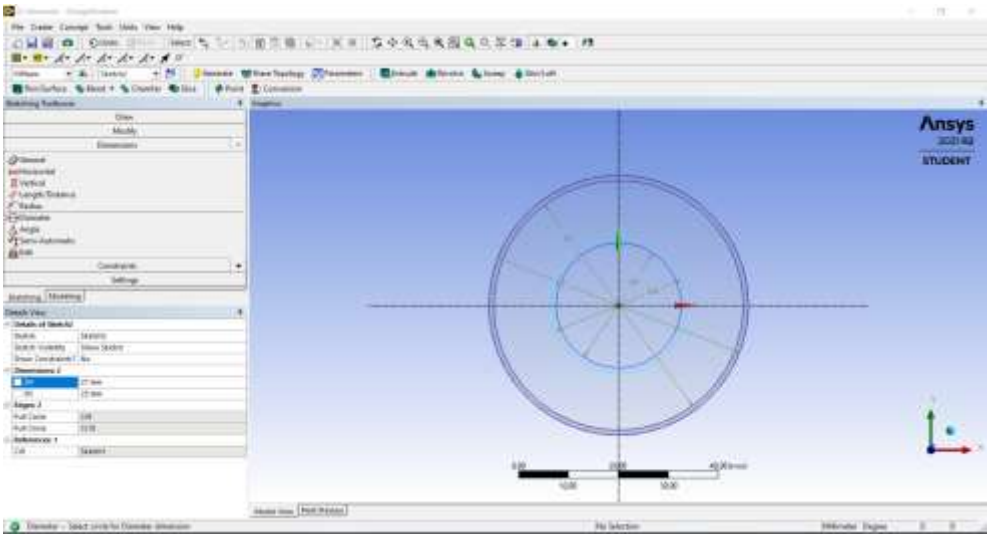
gelmektedir (Tiari ve Hockins 2021). Enerjinin pahalı olduğu ülkelerde ise ısıtılması istenilen yerlerde yerel olarak yapılmaktadır. Şekil 1.' de görüldüğü gibi ANSYS ortamında her bir iç boru geometrisi için proje şeması oluşturularak faz değiştiren malzemeler için analiz tasarlanmıştır.



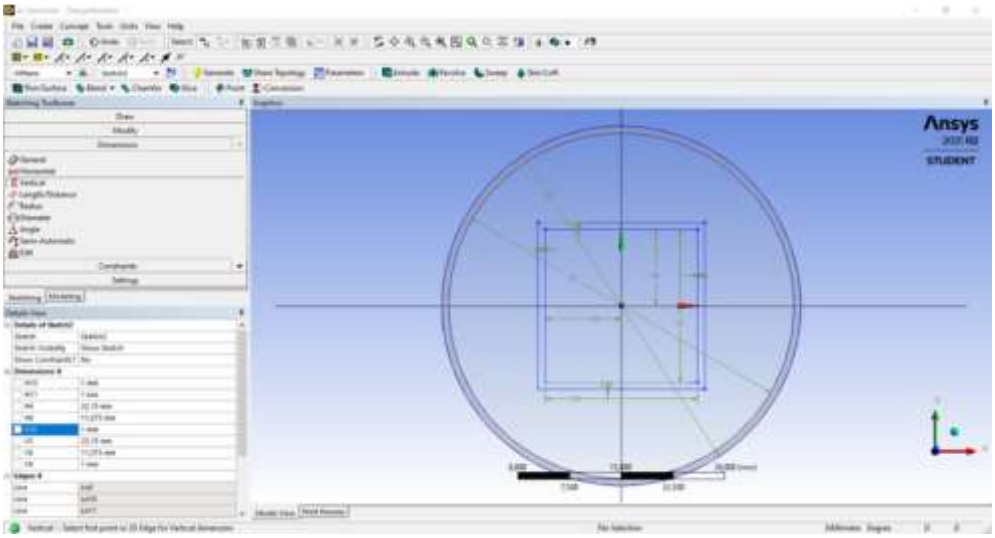
Şekil 1. ANSYS proje şeması

3.1. İç-Dış boru geometrisinin oluşturulması

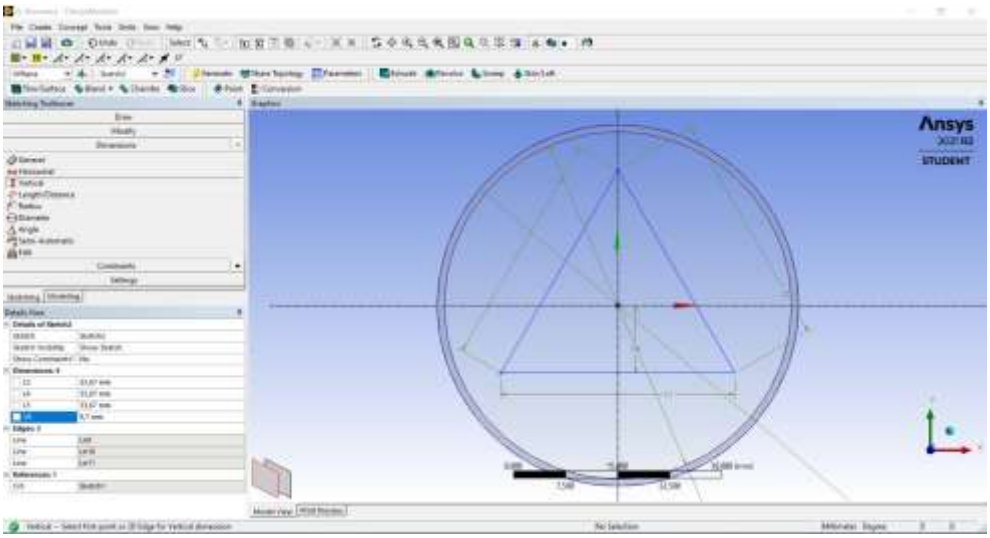
Boru iç çapı 50 mm, dış çapı 52 mm ve uzunluğu 1000 mm olarak verilmiştir. Dairesel iç boru geometrisi piyasada en çok kullanılan ve temin hızı yüksek olmasından dolayı 27 mm dış çapa ve 25 mm iç çapa sahip olacak şekilde ayarlanmıştır.



Şekil 2. Dairesel kesit iç boru ölçüleri



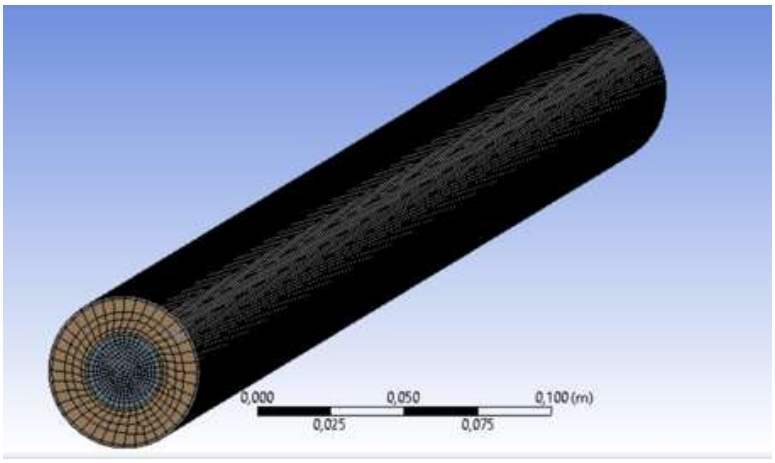
Şekil 3. Karesel kesit iç boru ölçüleri



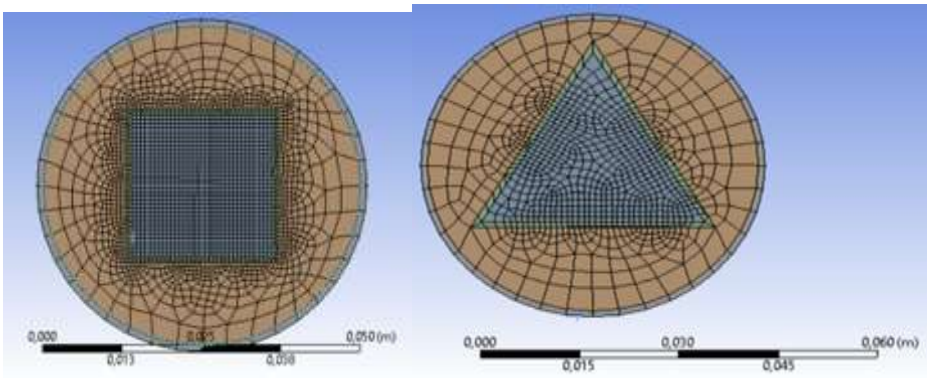
Şekil 4. Üçgensel kesit iç boru ölçüleri

3.2. Mesh İşlemi

Tasarımı yapılan geometrilerin analizin gerçeğe yakın sonuç vermesi için yapılması gereken en önemli aşamalardan biridir. Skewness değeri 0'a yakın ve ortogonal quality değeride 1'e yakın olduğu için analiz için makul kabul edilmiştir.



Şekil 5. Dairesel iç kesit görünümü



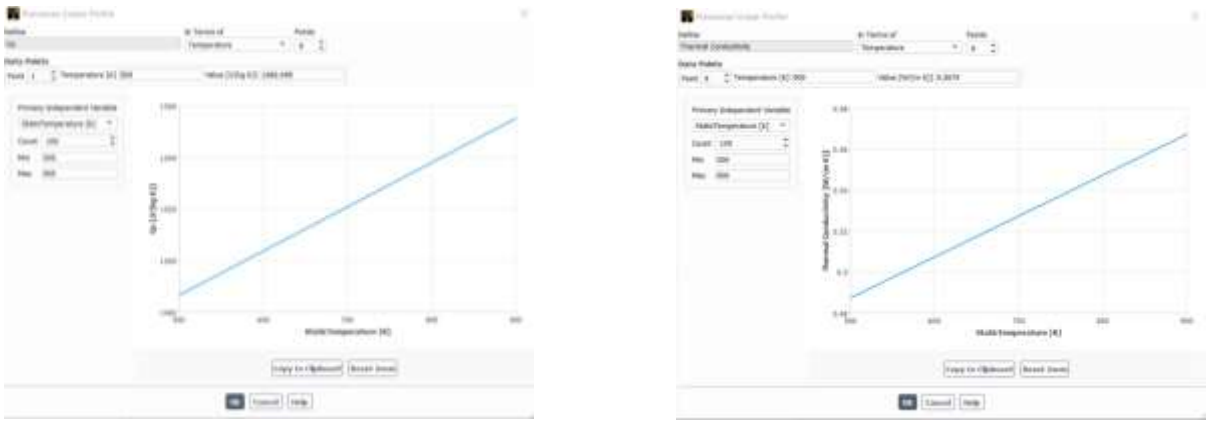
Şekil 6. Karesel ve üçgensel iç kesit görünümü

3.3. Fluent Analizi

Fluent programında FDM' lerin analizi için Solidification and Melting özelliği aktif hale getirilmiştir. Fluent ortamında malzeme seçimi ve tanımlanması yapılmıştır. Analizde kullanılan tüm malzemeler katı ve sıvı olmak üzere seçilerek işlem yapılmıştır.

Tablo 1. Erimiş Nitrat Özellikleri

Erimiş Nitrat Özellikleri						
S.No	Sıcaklık K	Sıcaklık C	Özgül Isı	Yoğunluk	İletim katsayısı	Viskozite
1	500	227	1486,4986	1945,628	0,4874	0,0053429
2	550	277	1495,0886	1913,828	0,4974	0,0037339
3	600	327	1503,6786	1882,028	0,5074	0,0027697
4	650	377	1512,2686	1850,228	0,5174	0,0021439
5	700	427	1520,8586	1818,428	0,5274	0,0017134
6	750	477	1529,4486	1786,628	0,5374	0,0014038
7	800	527	1538,0386	1754,828	0,5474	0,0011732
8	850	577	1546,6286	1723,028	0,5574	0,0009966
9	900	627	1555,2186	1691,228	0,5674	0,0008581



Şekil 7. Erimiş nitratın Fluent programına sıcaklığa bağlı Cp ve ısıl iletkenlik değerlerinin girilmesi

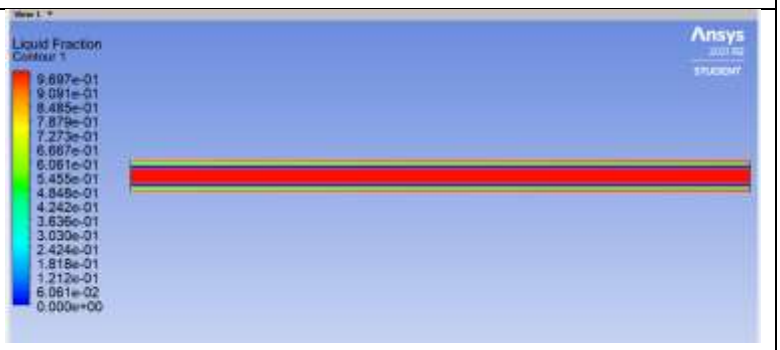
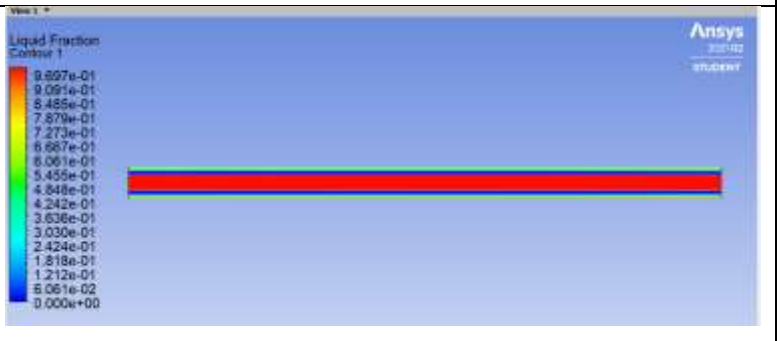
Fluent programına giren malzemenin kütlesel debisi 0,5 kg/s olarak girilmiştir. Ayrıca1 saniye aralıklarla çözüm için koşullar girilmiştir. Program çalıştırıldığında iterasyon sayısı işlemde geçen saniye olarak zamanı göstermektedir.

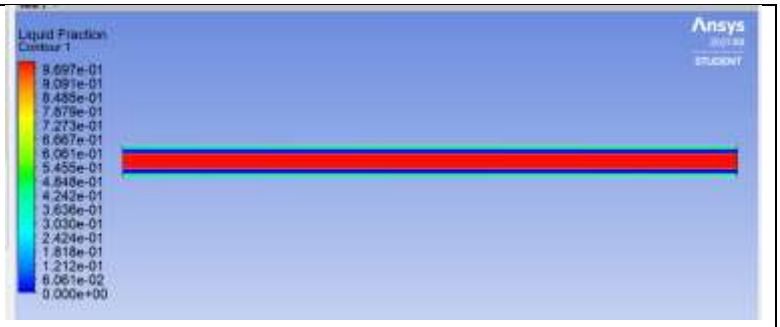
4. SONUÇLAR VE TARTIŞMA

Dairesel, karesel ve üçgensel iç borulu geometrinin 100,200 ve 300 saniye sonundaki miktarı gösterilmektedir.

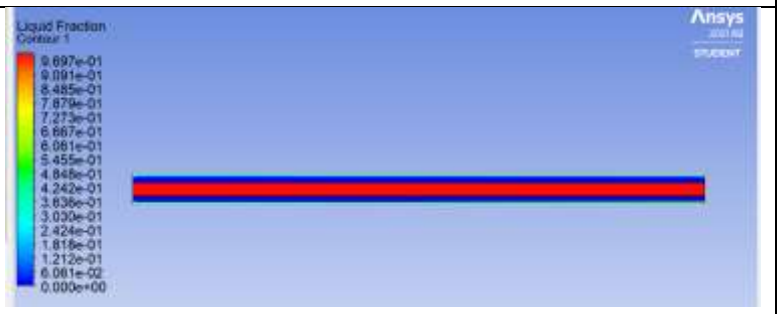
Fluent programında hesaplanan faz değiştiren malzeme ortalama değerlere göre Tablo 2-4.'de enine kesit alınarak boru boyunca değişimi gözlenmiştir.

Tablo 2. Dairesel iç boru sıvı miktarının enine kesit gösterimi

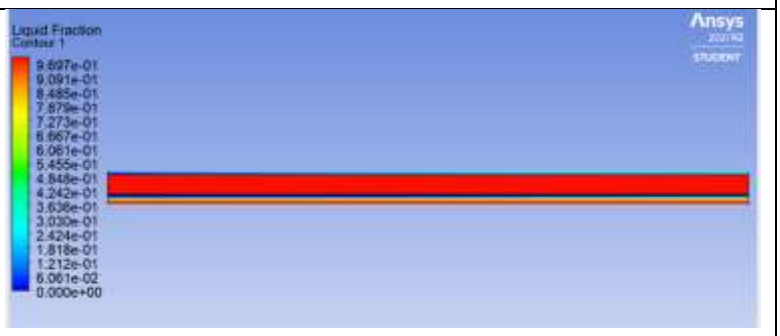
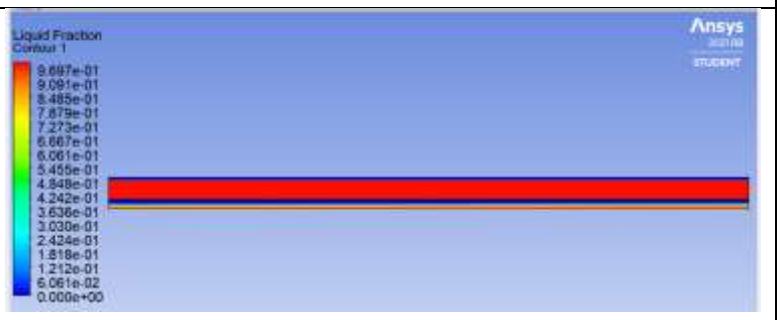
Sıvı miktarının enine kesit gösterimi	
Dairesel iç boru geometrisi için 100 saniyedeki verileri	
Dairesel iç boru geometrisi için 200 saniyedeki verileri	

Dairesel iç boru geometrisi için 300 saniyedeki verileri	

Tablo 3. Karesel iç boru sıvı miktarının enine kesit gösterimi

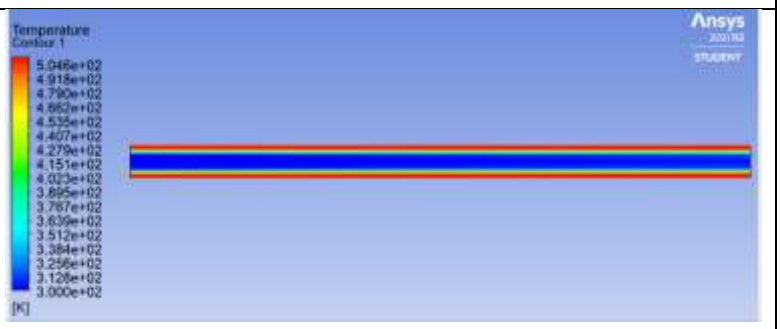
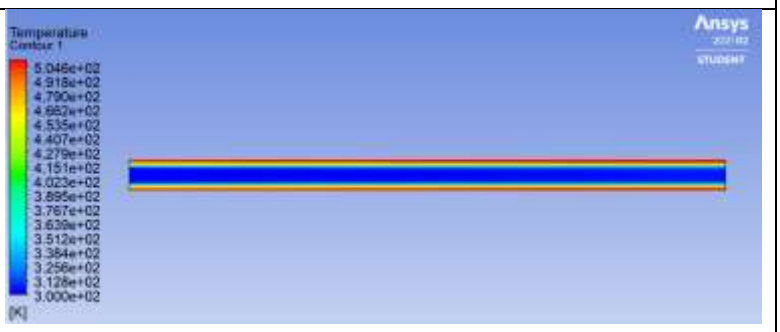
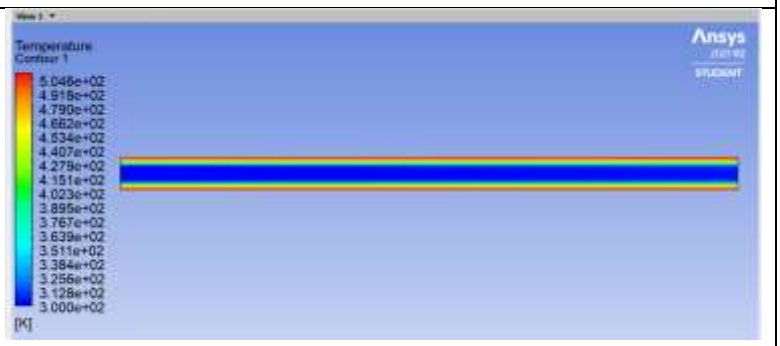
Sıvı miktarının enine kesit gösterimi	
Karesel iç boru geometrisi için 100 saniyedeki verileri	
Karesel iç boru geometrisi için 200 saniyedeki verileri	
Karesel iç boru geometrisi için 300 saniyedeki verileri	

Tablo 4. Üçgensel iç boru Sıvı miktarının enine kesit gösterimi

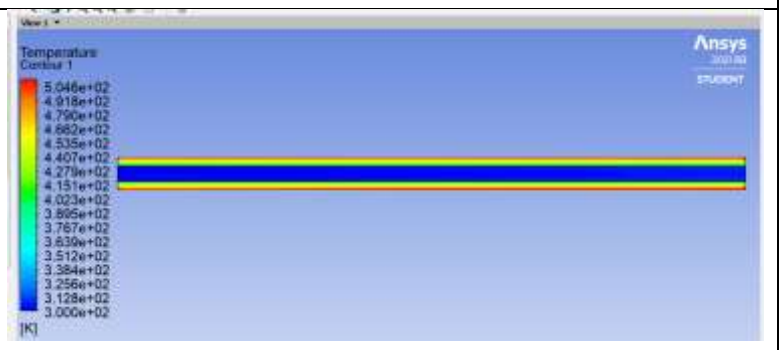
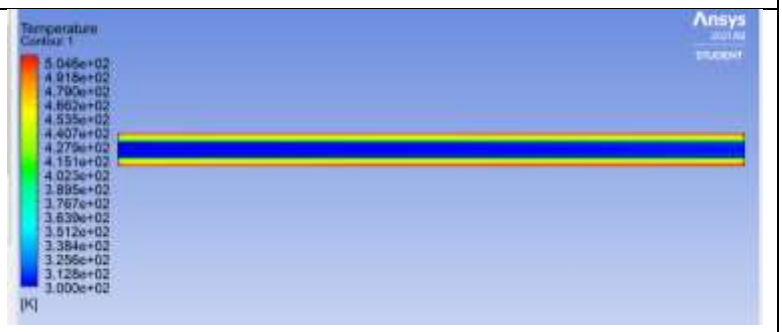
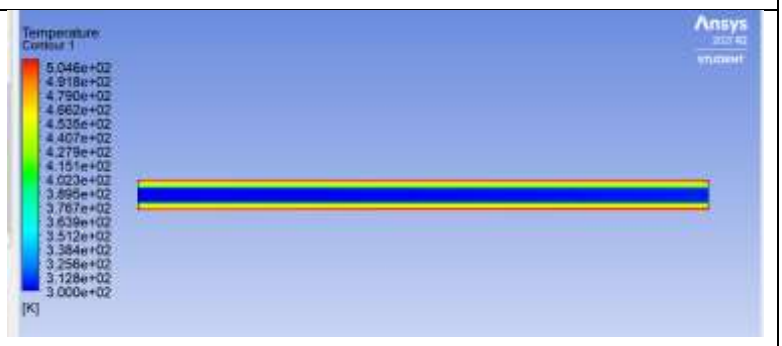
Sıvı miktarının enine kesit gösterimi	
Üçgensel iç boru geometrisi için 100 saniyedeki verileri	
Üçgensel iç boru geometrisi için 200 saniyedeki verileri	
Üçgensel iç boru geometrisi için 300 saniyedeki verileri	

Fluent programında hesaplanan faz değiştiren malzemenin sıcaklık ortalama değerleri göre Tablo 5-7.'de enine kesit alınarak boru boyunca değişimi gözlenmiştir.

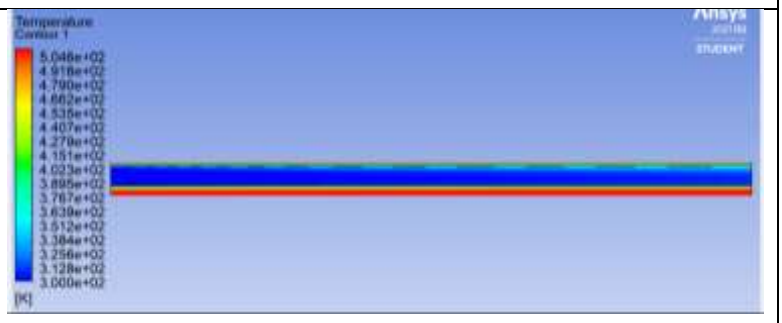
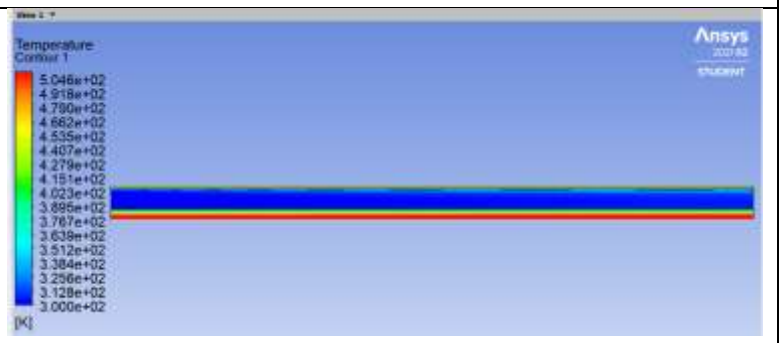
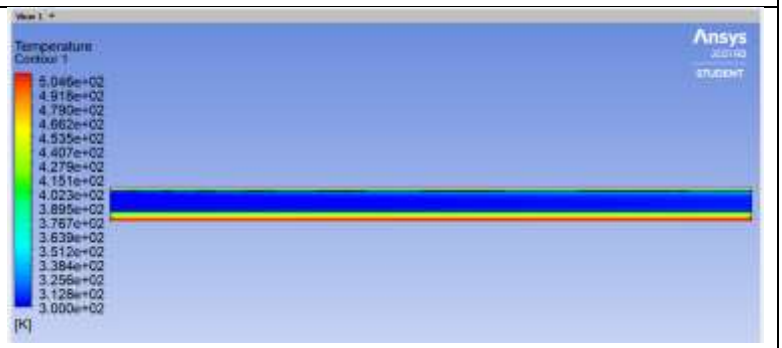
Tablo 5. Dairesel iç boru sıcaklığının enine kesit gösterimi

Sıcaklık dağılımının enine kesit gösterimi	
Dairesel iç boru geometrisi için 100 saniyedeki verileri	
Dairesel iç boru geometrisi için 200 saniyedeki verileri	
Dairesel iç boru geometrisi için 300 saniyedeki verileri	

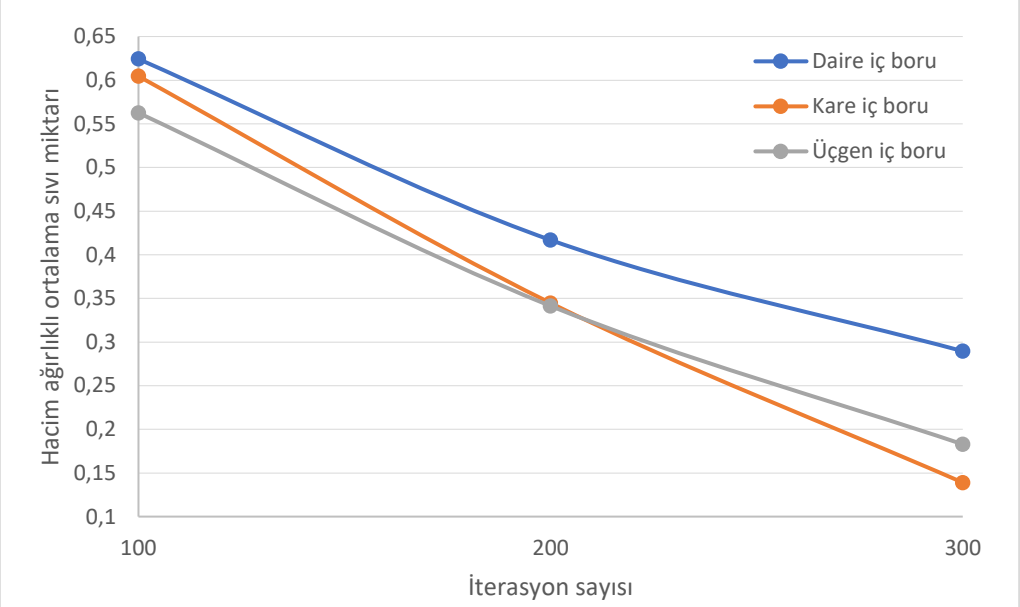
Tablo 6. Karesel iç boru sıcaklığının enine kesit gösterimi

Sıcaklık dağılımının enine kesit gösterimi	
Karesel iç boru geometrisi için 100 saniyedeki verileri	
Karesel iç boru geometrisi için 200 saniyedeki verileri	
Karesel iç boru geometrisi için 300 saniyedeki verileri	

Tablo 7. Üçgensel iç boru sıcaklığının enine kesit gösterimi

Sıcaklık dağılımının enine kesit gösterimi	
Üçgensel iç boru geometrisi için 100 saniyedeki verileri	
Üçgensel iç boru geometrisi için 200 saniyedeki verileri	
Üçgensel iç boru geometrisi için 300 saniyedeki verileri	

Bütün faz değiştiren malzemelere ait geometriler incelendiğinde Şekil 2.ve 5.'deki dairesel geometriye sahip iç borunun faz değiştiren malzemeler ile uygulanmasında aynı uzunluktaki eşit kesit alanlı karesel ve üçgensel boru geometrilerine Şekil 8.'e göre hacim ağırlıklı sıvı miktarı giriş-çıkış değerlerine göre daha verimliği olduğu analiz edilmiştir. Giriş-çıkış sıcaklık değerlerine bakıldığında da köşegen sayısına üçgensel geometrinin daha avantajlı olduğu tespit edilmiştir.



Şekil 8. İç boru geometrilerinin hacim ağırlıklı sıvı miktarı gösterimi

Tablo 8. Süreye göre iç boru geometrilerinin analiz sonuçları

İç Boru Geometri Tipi	100 iterasyon (100 Saniye)			200 iterasyon (200 Saniye)			300 iterasyon (300 Saniye)		
	Giriş Sıcaklığı [K]	Çıkış Sıcaklığı [K]	Hacim ağırlıklı ortalama sıvı miktarı	Giriş Sıcaklığı [K]	Çıkış Sıcaklığı [K]	Hacim ağırlıklı ortalama sıvı miktarı	Giriş Sıcaklığı [K]	Çıkış Sıcaklığı [K]	Hacim ağırlıklı ortalama sıvı miktarı
Daire	300	310,9694	0,62424248	300	307,4196	0,41686886	300	306,18542	0,28953728
Kare	300	313,5967	0,60452005	300	310,0119	0,34466738	300	309,46724	0,13899501
Üçgen	300	316,3081	0,56253723	300	311,1218	0,3413011	300	309,96638	0,18283422

Bu çalışmanın sonucuna göre ileride yapılacak deneysel çalışmalarda faz değiştiren malzemelerin fiziksel ve kimyasal özelliklerinin yanında geometrisinin de önemli olduğu ortaya çıkmıştır. Nükleer enerjinin önem arz etmesi itibariyle enerji üretimi ve tüketiminin öneminin logaritmik olarak arttığı çağımızda faz değiştiren malzemelere ve sistemlerine olan gereksinim artacaktır.

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CUPRESSUS TÜRLERİNİN UÇUCU YAĞLARININ KİMYASAL BİLEŞİMİ VE BİTKİ PATOJENLERİNE KARŞI ANTİMİKROBİYAL POTANSİYELİ

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ÖZET

Bitkisel kökenli uçucu yağlar, sekonder metabolitler olarak bitkilerde düşük miktarlarda bulunmalarına rağmen, zengin kimyasal çeşitlilikleri ve güçlü biyolojik aktiviteleri ile dikkat çekmektedir. Bu bağlamda, Cupressaceae familyasına ait *Cupressus* cinsi (servi ağaçları), sentetik pestisitlere çevre dostu ve sürdürülebilir bir alternatif olma potansiyeli taşıyan önemli bir doğal kaynak olarak öne çıkmaktadır. *Cupressus sempervirens* ve *C. arizonica* gibi türlerden elde edilen uçucu yağlar, genetik yapı ve çevresel koşullara bağlı olarak farklılık gösterse de genellikle α-pinen, δ-3-karen, sabinen ve terpinen-4-ol gibi biyoaktif monoterpenleri yüksek oranda içermektedir. Bu bileşenler, uçucu yağlara fungal ve bakteriyel bitki patojenlerine karşı çok yönlü antimikrobiyal mekanizmalar kazandırmaktadır. Başlıca etki mekanizmaları; patojen hücre zarının bütünlüğünü bozmak, geçirgenliği artırarak hücre içi bileşen kaybına yol açmak, ergosterol sentezini inhibe etmek ve biyofilm oluşumunu engellemektir. Deneysel bulgular, *Cupressus* türlerinden elde edilen uçucu yağların özellikle *Botrytis cinerea*, *Fusarium* spp. ve *Phytophthora* spp. gibi ekonomik öneme sahip fitopatojenlere karşı belirgin inhibisyon aktivitesi sergilediğini göstermektedir. Ayrıca bazı türlerin, bitki patojenlerinin yanı sıra çeşitli Gram pozitif ve Gram negatif bakteriler üzerinde de etkili olduğu bildirilmiştir. Sonuç olarak, *Cupressus* türlerine ait uçucu yağlar, modern tarımda bitki hastalıklarının biyolojik kontrolünde değerlendirilebilecek doğal ve çevre dostu bileşikler olarak önemli bir potansiyele sahiptir. Bu potansiyelin etkin biçimde değerlendirilebilmesi için, kimyasal profillerin standardizasyonu, formülasyon geliştirme ve etkinliğin hem kontrollü hem de tarla koşullarında test edilmesine yönelik ileri araştırmalara ihtiyaç duyulmaktadır.

Anahtar kelimeler: Cupressaceae, uçucu yağ, antimikrobiyal aktivite, *Cupressus* spp., bitki patojenleri

CHEMICAL COMPOSITION AND ANTIMICROBIAL POTENTIAL OF *CUPRESSUS* SPECIES ESSENTIAL OILS AGAINST PLANT PATHOGENS

ABSTRACT

Essential oils of plant origin, as secondary metabolites, are found in low amounts in plants; however, they attract attention due to their rich chemical diversity and potent biological activities. In this context, the *Cupressus* genus (cypress trees) of the Cupressaceae family stands out as an important natural resource with the potential to be an eco-friendly and sustainable alternative to synthetic pesticides. Although essential oils obtained from species such as *Cupressus sempervirens* and *C. arizonica* show variation depending on genetic structure and environmental conditions, they generally contain high levels of bioactive monoterpenes like α-pinene, δ-3-carene, sabinene, and terpinen-4-ol. These components provide the essential oils with multiple antimicrobial mechanisms against fungal and bacterial plant pathogens. The primary mechanisms of action include disrupting the integrity of the pathogen cell membrane, increasing permeability leading to the loss of intracellular components, inhibiting ergosterol synthesis, and preventing biofilm formation. Experimental findings indicate that essential oils derived from *Cupressus* species exhibit significant inhibitory activity against economically important phytopathogens such as *Botrytis cinerea*, *Fusarium* spp., and *Phytophthora* spp. Furthermore, some species have also been reported to be effective against various Gram-positive and Gram-negative bacteria, in addition to plant pathogens. In conclusion, the essential oils derived from *Cupressus* species possess significant potential as natural and environmentally friendly compounds that can be utilized in the biological control of plant diseases in modern agriculture. To effectively utilize this potential, further research is needed focusing on the standardization of chemical profiles, formulation development, and testing their efficacy under both controlled and field conditions.

Keywords: Cupressaceae, essential oil, antimicrobial activity, *Cupressus* spp., plant pathogens

1. GİRİŞ

Uçucu yağlar (esansiyel yağlar, EO), bitkilerin toplam biyokütlesinde düşük oranlarda bulunmalarına rağmen aromatik türlere özgü koku ve tat özelliklerinin temel belirleyicileridir. İçeriklerindeki yüzlerce biyoaktif bileşik, bu doğal ürünlerin hem kimyasal çeşitliliğini hem de biyolojik etkinliğini artırmaktadır. Kimyasal açıdan en baskın gruplar monoterpenler ve seskiterpenler olup, bunlara aldehit, keton, fenol, alkol, asetat ve oksit gibi oksijenli türevler eşlik eder. Bazı türlerde ester ve eterler de yüksek oranlarda bulunabilir. Bu farklılıklar, uçucu yağların duyusal özellikleri ve biyolojik aktivitelerini belirleyen başlıca faktörlerdir (Yousefi ve ark., 2019).

Tarımda yaygın olarak kullanılan sentetik fungisitler kısa vadede hastalıkları kontrol etse de zamanla dirençli patojen popülasyonlarının oluşmasına ve çevre ile insan sağlığına olumsuz etkiler yaratmaktadır (Elshafie ve ark., 2015). Bu durum, biyolojik olarak parçalanabilir, çevre dostu ve sürdürülebilir alternatiflerin önemini artırmıştır. Bu bağlamda bitkisel ekstraktlar ve uçucu yağlar doğal ve güvenli bir seçenek olarak öne çıkmaktadır (Vitoratos ve ark., 2013).

Son yıllarda, uçucu yağların doğal yapıları sayesinde antimikrobiyal kullanımına yönelik ilgi artmıştır. Çeşitli araştırmalar, bu bileşiklerin mevcut fungisitlerle karşılaştırılabilir, hatta bazı durumlarda daha üstün antimikrobiyal etki gösterebildiğini ortaya koymaktadır. Antifungal ve antibakteriyel aktiviteleri nedeniyle özellikle bitki patojenlerinin biyolojik kontrolünde umut vadeden bir alternatif olarak değerlendirilmektedir (Cano-Lamadrid ve ark., 2020).

Bilinen yaklaşık 300 bitki familyasının üçte biri uçucu yağ içerirken (Affes ve ark., 2022), bu türlerin yalnızca küçük bir bölümü biyopestisit olarak değerlendirilmiştir (Zhao ve ark., 2021). Uçucu yağların kimyasal yapılarında mentol, linalool, karvakrol, timol, borneol, α-pinen, sitral, öjenol ve d-limonen gibi terpenler yer almakta; bu bileşenler fungus ve bakterilerin gelişimini farklı mekanizmalarla baskılamaktadır. Terpenler bakterilerin ve fungal organizmaların zar yapısını bozmakta, membran geçirgenliğini artırmakta, DNA/RNA sentezini engellemekte ve metabolik aktiviteleri düşürmektedir (Türkkan ve ark., 2020; Guo ve ark., 2021; Han ve ark., 2021; Konuk ve Ergüden, 2022; Zareshahrabadi ve ark., 2023; Houzi ve ark., 2024). Böylece bitkilerin doğal savunma mekanizmalarının bir parçası olarak hem çevresel streslere hem de patojen saldırılarına karşı direnç geliştirmelerine katkı sağlarlar (Hammerbacher ve ark., 2019; Boncan ve ark., 2020; Khan ve ark., 2025).

Birçok familya (Asteraceae, Apiaceae, Lamiaceae, Myrtaceae, Rutaceae, Cupressaceae vb.) uçucu yağ bakımından zengin olup, bu yağlar gıda, kozmetik ve farmasötik alanlarda yaygın olarak kullanılmaktadır (Yeşilbağ, 2007; Fragkouli ve ark., 2023; Gladikostić ve ark., 2023; Önder ve ark., 2024). Bununla birlikte, artan sayıda araştırma, söz konusu yağların güçlü antifungal ve antibakteriyel özellikler sergileyerek tarımsal patojenlerin kontrolünde de değerlendirilebileceğini göstermektedir (Koçak ve Boyraz, 2006; Tapwal ve ark., 2011; Šernaitė ve ark., 2017; Sharma ve ark., 2017; Diánez ve ark., 2018; Jiménez-Reyes ve ark., 2019; Steglińska ve ark., 2022; Saygılı ve ark., 2025).

Cupressaceae familyası ve özellikle *Cupressus* türleri, uçucu yağ içeriği bakımından öne çıkan odunsu bitkilerdir. Bu türlerin yağlarında α-pinen, δ-3-karen, limonen ve borneol gibi monoterpenler ile çeşitli oksijenli bileşiklerin yüksek oranlarda bulunduğu bildirilmektedir (El Hamrouni-Aschi ve ark., 2013; Hosseinihashemi ve ark., 2023). *Cupressus* uçucu yağlarının antimikrobiyal etkinlikleri üzerine yapılan çalışmalar hem insan kaynaklı patojenler hem de bitki hastalık etmenleri üzerinde dikkate değer düzeyde engelleyici etki gösterdiğini ortaya koymaktadır. Özellikle *Cupressus sempervirens* ve *Cupressus macrocarpa* türlerinin uçucu yağları, çeşitli mikroorganizmaların gelişimini inhibe etme potansiyeline sahiptir (Mahmood

ve ark., 2013; Selim ve ark., 2014; Harfouch ve ark., 2022). Bu özellikler, *Cupressus* türlerinden elde edilen uçucu yağların bitki hastalıklarının biyolojik kontrolünde alternatif bir kaynak olabileceğini göstermektedir.

Bu derleme çalışmasında, *Cupressus* türlerinin uçucu yağlarının kimyasal bileşimleri, antimikrobiyal özellikleri ve bitki patojenlerine karşı kullanım potansiyelleri literatür verileri ışığında ele alınmıştır.

2. *Cupressus* Türlerinin Farmakolojik Özellikleri ve Antimikrobiyal Potansiyeli

2.1. Cupressaceae Familyası ve *Cupressus* Cinsi

Cupressaceae familyası, kozalaklı bitkiler (Coniferales) içerisinde en fazla cinse sahip familyalardan biri olup, tür çeşitliliği bakımından üçüncü sırada yer almaktadır. Günümüzde yaklaşık 30 cins ve 130–140 tür ile temsil edilmektedir. Bu familya içerisinde önemli bir yere sahip olan *Cupressus* cinsi, genellikle 5–40 metreye kadar boylanabilen, her dem yeşil ağaçlar veya büyük çalılar ile karakterizedir. Yaprak morfolojisi gelişim dönemine göre farklılık göstermekte olup, genç bireylerde iğne yapraklı, olgun bireylerde ise skala (pul) yapraklı formda bulunmakta ve karşılıklı dizilim göstermektedir (Schulz ve ark., 2005).

Bu cinsin üyeleri, doğal dağılımlarının çok ötesinde geniş coğrafi alanlarda süs bitkisi olarak da yaygın biçimde kullanılmaktadır (Peters ve ark., 2021). *Cupressus* türleri, çok yönlü kullanım alanlarına sahip olup dayanıklı odunları mobilya ve inşaat sektöründe, uçucu yağları ise parfümeri, kozmetik ve farmasötik endüstrilerde değerlendirilmektedir (Weick ve ark., 2023). Türkiye'de doğal olarak yetişen türler, sahip oldukları özellikler sayesinde hem ekonomik hem de ekolojik ve farmakolojik uygulamalara katkı sağlamaktadır (Uçar ve ark., 2019).

Cupressus uçucu yağlarının içerdiği biyoaktif bileşikler yalnızca tıbbi uygulamalarda değil, aynı zamanda fungal ve bakteriyel kaynaklı bitki hastalıklarının biyolojik kontrolünde de önemli bir potansiyel sergilemektedir (Toktaş ve ark., 2024). Bu nedenle *Cupressus* türleri, son yıllarda tarımsal biyoteknoloji ve bitki koruma araştırmalarında dikkat çeken doğal kaynaklar arasında yer almaktadır (Selim ve ark., 2014).

Bitki patojenleriyle ilişkili çalışmalarda özellikle *Cupressus sempervirens* (Akdeniz servisi) ve *Cupressus macrocarpa* (Limon servisi) türleri öne çıkmaktadır (Orhan ve Tumen, 2015). Bu türlerin uçucu yağları üzerine yapılan araştırmalar hem insan kaynaklı mikroorganizmalar hem de tarımsal öneme sahip bitki patojenleri üzerinde belirgin antimikrobiyal etkilere sahip olduklarını ortaya koymaktadır (Soltani ve Hosseyni Moghaddam, 2015; Hussain ve ark., 2019).

2.2. *Cupressus* Türlerinin Uçucu Yağlarının Kimyasal Bileşimi

Cupressus türlerinden elde edilen uçucu yağlar; bitki türüne, kullanılan bitki kısmına (özellikle yaprak ve nadiren odun) ve coğrafi kökene bağlı olarak değişken kimyasal bileşimler göstermektedir (Tablo 1).

Cezayir, Türkiye, Arjantin, Meksika ve Portekiz'de yürütülen çalışmalar, sekiz farklı *Cupressus* türünün uçucu yağ profillerini karşılaştırmalı olarak değerlendirmiştir. Çalışmalarda bildirilen bileşik sayısı 46 ile 54 arasında değişmektedir (Frezza ve ark., 2022).

Genel olarak, α-pinen sekiz türün tamamında en baskın bileşik olarak öne çıkmaktadır. Umbellulone ve terpinen-4-ol beş türde baskın veya ikincil bileşikler olarak rapor edilmiştir. Sabinen üç türde belirgin bir bileşen olarak saptanırken, abietadien, limonen, β-phellandrene, trans-totarol, butil metil eter ve δ-3-karen yalnızca iki türde baskın ya da ikincil konumda

bulunmuştur. Ayrıca karvakrol metileter, α-sedrol, α-terpinil asetat, cis-muurola-4(14),5-dien, filokladanol, nezukol, izofillokladen, trans-ferruginol, α-kadinol, p-simen ve manool gibi bileşikler ise yalnızca tek bir türde tespit edilmiştir (Malizia ve ark., 2000; Mazari ve ark., 2010). Üzerinde en çok araştırm yapılan türler arasında *Cupressus arizonica*, *Cupressus sempervirens* ve *Cupressus macrocarpa* yer almaktadır (Frezza ve ark., 2022).

Tablo 1. *Cupressus* türlerinin uçucu yağ bileşenleri, oranları (%) ve analiz yöntemleri

Tür	Baskın bileşikler	Oran (%)	Yöntem	Kaynak
***Cupressus sempervirens* (Akdeniz servisi)**	α-pinen, δ-3-karen, limonen, sabinen	α-pinen %35–50, δ-3-karen %15–25	Hidrodistilasyon, GC-MS	El Hamrouni-Aschi ve ark., 2013; Mahmood ve ark., 2013
	Karvakrol metileter, α-sedrol, manool, terpinen-4-ol asetat, borneol asetat	Karvakrol metileter %38,2–62,6; α-sedrol %15,7–34,3	GC-MS	Uçar ve ark., 2019
***Cupressus macrocarpa* (Limon servisi)**	α-pinen, limonen, terpinolen, myrcene	α-pinen %20–40, limonen %10–20	Hidrodistilasyon, GC-MS	Bezić ve ark., 2011; Hosseinihashemi ve ark., 2023
	Terpinen-4-ol, α-pinen, sabinen, p-simen	Terpinen-4-ol %29,6; α-pinen %20,2; sabinen %12,0	GC-MS	Malizia ve ark., 2000
***Cupressus arizonica* (Arizona servisi)**	Sabinen, α-pinen, β-pinen, limonen	Sabinen %25–35; α-pinen %15–20	GC-MS	Selim ve ark., 2014
	cis-muurola-4(14),5-dien, α-pinen, umbellulone, limonen, terpinen-4-ol	cis-muurola-4(14),5-dien %90; α-pinen %22,9; umbellulone %16,5	GC-MS	Malizia ve ark., 2000
	Filokladanol, butil metil eter, nezukol, α-pinen, β-phellandrene, umbellulone, isophyllocladene	Filokladanol %14,2; α-pinen %7,6	GC-MS	Adams ve ark., 1997
***Cupressus lusitanica* (Meksika servisi)**	α-pinen, sabinen, bornil asetat, terpinen-4-ol	α-pinen %30; sabinen %25	GC-MS	Harfouch ve ark., 2022
	Abietadien, α-pinen, sabinen, trans-totarol	Abietadien %11–24; α-pinen %6,0–16,6	GC-MS	Adams ve ark., 1997
***Cupressus torulosa* (Himalaya servisi)**	α-pinen, δ-3-karen, borneol	α-pinen %40'a kadar	GC-MS	Soltani ve Hosseyni Moghaddam, 2015
	α-pinen, sabinen, terpinen-4-ol, α-tujen, mirsen	α-pinen %25,8; sabinen %22,3	GC-MS	Malizia ve ark., 2000
Cupressus glabra	Umbellulone, terpinen-4-ol	Umbellulone %27,4; terpinen-4-ol %10,5	GC-MS	Chanegriha ve ark., 1997
Cupressus benthamii	Abietadien, trans-totarol, α-pinen, cis-totarol, trans-ferruginol	Abietadien %26; trans-totarol %19,3	GC-MS	Adams ve ark., 1997
Cupressus lindleyi	Limonen, β-phellandrene, α-cadinol, butil metil eter, umbellulone, terpinen-4-ol	Limonen %14,0; β-phellandrene %13,0	GC-MS	Adams ve ark., 1997

Cupressus türleri arasında belirgin kimyasal çeşitlilik gözlenmektedir ve bu çeşitlilik çoğunlukla türün genetik yapısı, coğrafi kökeni, kullanılan bitki dokusu (yaprak, odun, kozalak vb.) ve ekstraksiyon yöntemi gibi faktörlerden etkilenmektedir. Tüm türlerde ortak baskın bileşik olarak tanımlanan α-pinen, hem biyolojik aktivitenin temel belirleyicisi hem de kimyasal bir belirteç olarak önem taşımaktadır (Borges ve ark., 2019).

Tür içi varyasyonlarda, *C. sempervirens* yaprak yağının α-pinen içeriği %2,8–44,9 arasında değişmiş olup, bu durum kimyasal farklılıklarını ve çevresel-genetik etkileri düşündürmektedir. Türler arası farklılıklarda *C. glabra* ve *C. arizonica* umbellulone bakımından, *C. torulosa* α-pinen ve δ-3-karen yönünden, *C. macrocarpa* ise yüksek terpinen-4-ol içeriğiyle öne çıkmaktadır. Ayrıca *C. benthamii* ve *C. lusitanica*, abietadien ve trans-totarol içeriğiyle dikkat çekmektedir (Tablo 1). Bu kimyasal çeşitlilik, biyolojik aktivitede tür spesifik farklılıkların ortaya çıkmasına yol açmaktadır (Uçar ve ark., 2019).

Bu bulgular, *Cupressus* türlerinden elde edilen uçucu yağların biyolojik aktivite potansiyellerinin türden türe farklılık gösterebileceğini ve bu farklılığın, içerikteki özgül bileşiklerin varyasyonuna bağlı olabileceğini ortaya koymaktadır (Kapadia ve ark., 2022). Bu nedenle, uçucu yağların bitki patojenlerine karşı biyokontrol etkinliği değerlendirilirken, kimyasal bileşimin detaylı biçimde belirlenmesi büyük önem taşımaktadır.

Gelecekteki çalışmaların, çevresel koşulların, bitki dokusu tipinin ve ekstraksiyon yöntemlerinin uçucu yağ bileşimi üzerindeki etkilerini kapsamlı biçimde değerlendirmesi; ayrıca türler arası kimyasal bileşim farklılıklarının biyolojik aktivite ile korelasyonunun ortaya konması, *Cupressus* türlerinin biyoteknolojik ve tarımsal uygulamalardaki potansiyellerini daha net biçimde tanımlamaya katkı sağlayacaktır.

3. *Cupressus* türlerinin Antimikrobiyal Potansiyeli

3.1. *Cupressus* Uçucu Yağlarının Antimikrobiyal Etki Mekanizmaları

Cupressus türlerinden elde edilen uçucu yağların antimikrobiyal etkileri, içeriklerinde yoğun olarak bulunan monoterpenler (ör. α-pinen, δ-3-karen, sabinen, limonen) ve oksijenli türevler (ör. terpinen-4-ol, borneol, trans-totarol) ile ilişkilendirilmektedir. Bu bileşikler hem fungal hem de bakteriyel patojenler üzerinde farklı biyomoleküler mekanizmalarla etki göstermektedir (Nazzaro ve ark., 2017).

3.1.1. Fungal Patojenlere Karşı Etki Mekanizmaları

Cupressus uçucu yağları, fungal hücrelerinin yapısal ve metabolik süreçlerine çok yönlü müdahalelerle etki eder. Lipofilik özellikleri sayesinde fungal hücre zarına entegre olarak zar bütünlüğünü bozar, hifal yapılarda deformasyonlara yol açar ve iyon sızıntısını artırır (Taweechaisupapong ve ark., 2012).

1. Hücre duvarı sentezinin inhibisyonu

Terpenoid ve fenolik bileşikler, kitin ve β-glukan sentezini baskılayarak hücre duvarı bütünlüğünü zayıflatır (Lagrouh ve ark., 2017).

2. Hücre zarı ve ergosterol sentezinin hedeflenmesi

Monoterpenler, fungus zarının lipid tabakasına entegre olarak membran geçirgenliğini artırır. Ergosterol sentezinin baskılanması ile zar bütünlüğü kaybolur, iyon sızıntısı ve metabolit kaybı gerçekleşir (Ben Ghnaya ve ark., 2013).

3. Mitokondriyal fonksiyonların bozulması

Elektron taşıma zincirinin zarar görmesi ATP üretimini azaltır, ROS birikimine neden olur (Ankri ve Mirelman, 1999).

4. Genetik materyal üzerine etki

Fenolik bileşikler DNA ve RNA'ya bağlanarak replikasyon ve transkripsiyonu bozmakta, bu da spor oluşumu ve çimlenme gibi gelişimsel süreçlerin engellenmesine neden olmaktadır (Dambolena ve ark., 2013).

5. Biyofilm oluşumunun inhibisyonu

Uçucu yağ bileşikleri biyofilm gelişimini baskılayarak patojenlerin yüzeye tutunmasını engeller (Nazzaro ve ark., 2017). Bu çok yönlü mekanizmalar, *Cupressus* uçucu yağlarının bitki patojenlerine karşı biyokontrol potansiyelini güçlendirmektedir.

3.1.2. Bakteriyel Patojenlere Karşı Etki Mekanizmaları

Cupressus uçucu yağlarının bakteriler üzerinde de güçlü antimikrobiyal mekanizmalar sergilediği rapor edilmiştir. Bu yağlar, bakteri gelişimini baskılamakla kalmaz; aynı zamanda bitkilerde savunma sinyalizasyonunu da güçlendirir (Dorman ve Deans, 2000; Guimarães ve ark., 2019). Uçucu yağların Gram pozitif ve Gram negatif bakteriler de dahil olmak üzere geniş bir bakteri spektrumuna karşı etkili olduğu bildirilmiştir. Özellikle bakteri hücre zarını parçalayarak geçirgenliği artırdığı, fenilpropanoidler ve terpenoidler gibi ile lipofilik yapıları sayesinde bakteri hücre duvarında delikler açarak hücre bütünlüğünü bozduğu belirtilmiştir (Zengin ve Baysal, 2014).

1. Hücre zarının bozulması: α-pinen ve sabinen gibi monoterpenler zar geçirgenliğini artırır (Zore ve ark., 2011; Melkina ve ark., 2021).

2. Enerji metabolizmasının baskılanması: Proton gradyanının ortadan kalkması ATP üretimini azaltır (Nazzaro ve ark., 2013; Falleh ve ark., 2025).

3. Enzim ve protein inhibisyonu: Terpinen-4-ol ve borneol gibi oksijenli bileşikler, bakteri metabolizmasında rol alan enzimlere bağlanarak onların aktivitesini engelleyebilir (Zhang ve ark., 2018; Yuan ve ark., 2023).

4. Quorum sensing ve biyofilm inhibisyonu: α-pinen ve terpinen-4-ol, hücreler arası iletişimi bozarak biyofilm oluşumunu engeller (Khan ve ark., 2018).

5.Antimikrobiyal uzaklaştırma mekanizmalarının baskılanması: Direnç mekanizmalarında rol alan protein taşıyıcı sistemlerin inhibisyonu, bakterilerin savunma kapasitesini zayıflatır (Haque ve ark., 2016; Agreles ve ark., 2021). Özellikle *C. sempervirens* uçucu yağında bulunan α-pinen ve sedrol bileşiklerinin bakteriyel biyofilmi bozduğu, bakterilerin yüzeye tutunmasını engellediği ve hücre canlılığını azalttığı bildirilmiştir (Al-Mijalli ve ark., 2023). Bu bulgular, *Cupressus* türlerinin bakteriyel patojenlere karşı biyokontrol potansiyeline sahip olduğunu göstermektedir.

3.2. *Cupressus* Türlerinin Bitki Patojenlerine Karşı Kullanım Potansiyeli

Uçucu yağlar, bitkileri patojenlerden korumada doğal, çevre dostu ve sürdürülebilir alternatifler olarak giderek artan bir ilgi görmektedir. *Cupressus* türlerinden elde edilen uçucu yağlar, içeriklerindeki monoterpen ve fenolik bileşikler sayesinde hem fungal hem de bakteriyel fitopatojenlere karşı çok yönlü etki mekanizmaları sergilemektedir. Bitkisel uçucu yağların antimikrobiyal etkileri, bileşimlerinde bulunan cineol, kafur, linalool, α- ve β-pinen, borneol, limonen, karvakrol ve α-terpinen gibi bileşiklerle ilişkilendirilmektedir (Ríos, 2016). Bu bileşiklerin hidrofobik özellikleri, patojen hücre zarına nüfuz ederek zar geçirgenliğini artırmakta, iyon dengesini bozmakta ve hücre ölümüne yol açmaktadır. Ayrıca uçucu yağlar, fungal patojenlerde misel gelişimini yavaşlatmakta ve spor çimlenmesini engellemektedir (Buchbauer ve Baser, 2010). Bu mekanizmalar, *Cupressus* türlerinden elde edilen uçucu

yağların bitki patojenlerine karşı biyokontrol potansiyelini açıklamakta ve bu türlerin doğal antifungal ajanlar olarak kullanılabileceğini göstermektedir (Assadpour ve ark., 2023).

Örnek olarak, *Cupressus arizonica* var. *glabra* (Carolina Sapphire) bitkisinin farklı organlarından elde edilen uçucu yağlar GC ve GC-MS ile analiz edilmiştir. En baskın bileşik α-pinen (%20,7–68,5) olup, limonen, umbellulone, myrcene ve zonarene gibi diğer monoterpenler de belirgin oranlarda bulunmuştur. Bu yağlar, çilek antraknozu etmenleri *Colletotrichum acutatum, C. fragariae* ve *C. gloeosporioides* üzerinde değerlendirilmiş ve yalnızca odun-kabuk fraksiyonu orta düzeyde antifungal etki göstermiştir (Ali ve ark., 2013). Benzer şekilde Pansera ve ark. (2023), *C. sempervirens* yapraklarından elde edilen uçucu yağın kimyasal bileşimini ve *Colletotrichum fructicola* üzerindeki etkilerini incelemiş; β-thujen (%31,4) baskın bileşik olarak belirlenmiş ve uçucu yağ konidiyum çimlenmesini %50 oranında inhibe etmiş, 2 $\mu L \cdot mL^{-1}$ dozunda hiflerde morfolojik bozulmalar gözlenmiştir.

Cupressus arizonica uçucu yağları ayrıca fitopatojen oomycetlere karşı da etkilidir. Yapraklardan elde edilen yağda baskın bileşikler limonen (%23,3) ve α-pinen (%20,5) olup, *Phytophthora* türleri (*P. quercina, P. ×cambivora, P. plurivora*) üzerinde %0,5–%1 konsantrasyonlarda neredeyse tam koloni inhibisyonu sağlamıştır (Milanović ve ark., 2024).

C. sempervirens uçucu yağı hem fungal hem de bakteriyel mikroorganizmalara karşı geniş spektrumlu antimikrobiyal aktivite göstermektedir. İğne ve sürgünlerden buhar distilasyonu ile elde edilen yağ, *Aspergillus niger, A. flavus, A. fumigatus, Fusarium solani, F. oxysporum* ve *Penicillium digitatum* üzerinde yüksek inhibisyon sağlamış, *E. coli, Bacillus lactis* ve *Micrococcus luteus* gibi bakteriler üzerinde de etkili olmuştur (Mahmood ve ark., 2013).

C. sempervirens uçucu yağı, *Aspergillus flavus* ve *Fusarium oxysporum* üzerinde orta düzeyde baskı sağlarken, *Rhizopus stolonifer* üzerinde belirgin etki göstermemiştir. Aktivitenin büyük kısmı α-pinen, β-fellandren, α-terpinil asetat ve sedrol gibi majör bileşiklerden kaynaklanmakta, düşük orandaki bileşikler ise sinerjik etki ile katkıda bulunmaktadır (Mazari ve ark., 2010). Ismail ve ark. (2013), *C. sempervirens* uçucu yağının *Fusarium culmorum, F. oxysporum, F. equiseti, F. verticillioides, F. nygamai, Botrytis cinerea, Microdochium nivale* var. *nivale* ve *Alternaria* sp. üzerinde belirgin inhibitör etki gösterdiğini, *B. cinerea* üzerinde düşük konsantrasyonlarda bile etkili olduğunu rapor etmişlerdir.

C. sempervirens uçucu yağının kimyasal bileşimi ve antifungal etkisi, toplam bileşimin %98,9'unu oluşturan 39 bileşikle incelenmiştir. Monoterpen hidrokarbonlar (%90,7) baskın olup, başlıca bileşenler α-pinen (%40,5) ve δ-3-karen (%24,4) olarak belirlenmiştir. *Penicillium citrinum, B. cinerea* ve *A. flavus* türlerine karşı değişen konsantrasyonlarda inhibisyon gözlenmiş ve en yüksek inhibisyon *P. citrinum* için 500 µL/mL'de (7,67 mm), *B. cinerea* için 62,5 µL/mL'de (8,67 mm) ve *A. flavus* için 500 µL/mL'de (7,33 mm) kaydedilmiştir (Galovičová ve ark., 2023).

Bitkinin farklı fenolojik aşamaları dikkate alınarak elde edilen *C. sempervirens* uçucu yağları, α-pinen, β-karyofillen ve α-cedrol gibi bileşikler sayesinde *B. cinerea* misel gelişimini etkili şekilde baskılamaktadır. Çiçeklenme aşamasında elde edilen yağlar in vitro testlerde en yüksek antifungal aktiviteyi göstermiş ve mikroskobik incelemede konidiyumlarda şişme ve parçalanma gözlenmiştir. 1 mg/mL konsantrasyonda domates meyvelerine uygulanan yağ, hasat sonrası *B. cinerea* enfeksiyonunu %54 oranında inhibe ederek güvenli bir biyokontrol potansiyeli sunmaktadır (Rguez ve ark., 2018).

Cupressus türlerinin uçucu yağları, antimikrobiyal etkilerinin yanı sıra tohum çimlenmesi ve fide gelişimi üzerinde de etkili olabilmektedir. Örneğin, *C. sempervirens* uçucu yağı, kışlık buğday ve mısır tohumları üzerinde *Fusarium* türlerine karşı belirli düzeyde patojen kontrolü

sağlamıştır (Danielewicz ve ark., 2024). Ayrıca, 0,5 mg/mL konsantrasyonunda *B. cinerea* miselyumunu tamamen inhibe ederek *Alternaria alternata* ve *Penicillium italicum* üzerinde de yüksek inhibisyon sağlamıştır (Allagui ve ark., 2023).

C. sempervirens yapraklarından elde edilen uçucu yağda başlıca bileşikler sabinen (%67,46), 3-thujin (%8,50) ve 4-terpineol (%5,01) olup, *Verticillium* ve *Aspergillus* türlerine karşı antimikrobiyal aktivite göstermektedir (Azzaz ve ark., 2019).

Mevcut literatür incelendiğinde, *Cupressus* türlerinin antibakteriyel aktivitelerine ilişkin çalışmaların çoğunlukla tıbbi veya klinik öneme sahip bakteriler üzerinde yoğunlaştığı görülmektedir. Özellikle *Staphylococcus aureus*, *Escherichia coli*, *Salmonella typhimurium*, *Klebsiella pneumoniae* ve *Pseudomonas aeruginosa* gibi klinik patojenlere karşı yüksek düzeyde inhibisyon oranları rapor edilmiştir (Chaudhary ve ark., 2014; Al-Rajhi ve ark., 2023; Al-Mijalli ve ark., 2023). Yapılan çalışmalar, *Cupressus sempervirens*'in antibakteriyel özellikleri bakımından doğal bir biyolojik ajan olarak önemli potansiyele sahip olduğunu göstermektedir. Uçucu yağın başlıca bileşenleri δ-3-karen, D-limonen ve α-pinen olup, düşük minimum inhibisyon konsantrasyonlarında bakterisidal etki göstermekte; bakteri zar bütünlüğünü bozarak protein sızıntısına neden olmakta ve antibiyofilm aktivitesi sergilemektedir (Al-Mijalli ve ark., 2023; Argui ve ark., 2021). Metanol, etanol ve etil asetat yaprak özleri *S. aureus*, *Bacillus subtilis*, *P. aeruginosa*, *E. coli*, *K. pneumoniae* ve *S. typhimurium* türlerine karşı antimikrobiyal etki göstermiş; en yüksek aktivite metanol özlerinde gözlemlenmiştir (Chaudhary ve ark., 2014). Ayrıca, kozalaklardan elde edilen uçucu yağların hem Gram pozitif hem de Gram negatif bakterilere karşı belirgin antibakteriyel etki sergilediği bildirilmiştir (Al-Mouhajer ve ark., 2017). Benzer şekilde, *C. sempervirens* uçucu yağının geniş bir bakteri yelpazesinde aktivite gösterdiği, *P. aeruginosa*, *Salmonella enterica*, *Yersinia enterocolitica*, *B. subtilis*, *Enterococcus faecalis* ve *S. aureus* türlerine karşı etkili olduğu belirtilmiştir (Galovičová ve ark., 2023). Ayrıca *C. sempervirens* yağının *Verticillium* ve *Aspergillus* gibi mantarlar üzerinde inhibisyon potansiyeli sergilediği; bunun yanı sıra *E. coli*, *S. aureus* ve *B. subtilis* gibi bakterilere karşı da değişen düzeylerde antibakteriyel aktivite gösterdiği, en duyarlı türün *B. subtilis* olduğu, *E. coli*'nin ise daha dirençli kaldığı bildirilmiştir (Azzaz ve ark., 2019).

Bununla birlikte, fitopatojen bakteriler üzerine yürütülmüş çalışmalar oldukça sınırlıdır. *Cupressus* türlerinin zengin monoterpen ve fenolik bileşik içerikleri, *Pseudomonas syringae*, *Xanthomonas campestris*, *Agrobacterium tumefaciens* ve *Ralstonia solanacearum* gibi ekonomik öneme sahip bitki patojenlerine karşı da potansiyel antimikrobiyal aktivite gösterebileceğini düşündürmektedir. Ancak bu etkiye ilişkin deneysel kanıtlar henüz sınırlı düzeydedir. Bu nedenle, klinik bakterilerde saptanan güçlü antibakteriyel etkinin, gelecekte yapılacak fitobakteriyel patojenlere yönelik *in vitro* ve *in vivo* çalışmalar ile desteklenmesi, *Cupressus* türlerinin bitki sağlığında biyokontrol ajanı olarak değerlendirilmesine bilimsel temel oluşturacaktır.

4. SONUÇ

Cupressaceae familyasına ait *Cupressus* türlerinin uçucu yağları, günümüz tarımında sentetik pestisitlere alternatif oluşturabilecek önemli biyoaktif kaynaklar olarak öne çıkmaktadır. Yapılan araştırmalar, bu türlerden elde edilen uçucu yağların kimyalarında baskın olarak bulunan α-pinen, δ-3-karen, sabinen ve terpinen-4-ol gibi monoterpenik bileşiklerin, çeşitli fitopatojen mikroorganizmalar üzerinde kayda değer inhibisyon etkisi gösterdiğini ortaya koymuştur.

Söz konusu uçucu yağların antimikrobiyal etki mekanizmaları incelendiğinde, patojen hücre duvarı ve zar bütünlüğünün bozulması, iyon geçirgenliğinin artması, hücre içi komponentlerin dengesinin kaybolması ve biyofilm oluşumunun engellenmesi gibi çoklu hedeflere yönelik etkileri dikkat çekmektedir. Özellikle *Botrytis cinerea, Fusarium* türleri ve *Phytophthora* gibi ekonomik açıdan önemli patojenler üzerinde gösterdikleri yüksek etkinlik, bu yağların biyopestisit olarak kullanım potansiyelini destekler niteliktedir.

Ancak, *Cupressus* uçucu yağlarının ticari anlamda güvenilir biyokontrol ajanlarına dönüştürülebilmesi için öncelikle kimyasal içerik standardizasyonunun sağlanması, uygun formulasyon stratejilerinin geliştirilmesi ve etkinliklerinin gerçek tarımsal koşullarda doğrulanması gerekmektedir. Bu kapsamda yürütülecek multidisipliner çalışmalar, söz konusu doğal ürünlerin sürdürülebilir tarım sistemleri içindeki yerinin güçlendirilmesine katkı sağlayacaktır.

5. KAYNAKLAR

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WEED MANAGEMENT IN REGENERATIVE AND ORGANIC AGRICULTURE

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ABSTRACT

Managing weeds is a major problem that constantly appears in both regenerative and organic farming systems, where synthetic herbicide bans necessitate the creation of new, alternative, ecological methods. In contrast to conventional farming that is still largely reliant on chemical inputs, regenerative and organic farming systems implement ecological principles such as increasing biodiversity, improving soil health, and making the ecosystem more resilient. This article deeply examines the methods of weed control in regenerative and organic farming along with their biological bases, feasibility, and effects on the environment. The article looks at the natural mechanisms that regulate weed populations, among them allelopathy, competition, microbial symbioses, and nutrient cycling. It is particularly emphasized that soil microbial communities through plant–microbe signaling and rhizosphere-mediated suppression can be the major force in weed dynamics. The integration of cultural, mechanical, and biological methods—such as crop rotation, mulching, cover cropping, and microbial inoculation—is at the heart of sustainable weed management in these systems. Besides that, the newest inventions like biochar applications, allelopathic crop breeding, and AI-assisted mechanical weeding being compatible with ecological intensification is a nice touch of technological innovation. A comparative study allows one to say that regenerative and organic systems can cause higher short-term weed pressure, whereas long-term ecological benefits such as improved soil fertility, less erosion, increased biodiversity, and lower carbon footprints are their advantages. The article argues that sustainable weed management should not be regarded as the complete removal of unwanted plants but rather as their biological control within resilient agroecosystems. Understanding weed ecology from a systems perspective that involves biological, technological, and socio-economic aspects will be vital in providing global food security and climate resilience of the future.

Keywords: Regenerative agriculture, Organic farming, Weed ecology, Soil microbiome, Cover crops

INTRODUCTION

Weeds are one of the most tenacious and costly problems that significantly reduce global crop productivity. They not only compete with crops for essential resources such as light, water, nutrients, and space but also act as reservoirs for pests and pathogens (Liebman & Davis, 2000). To address the problem, the conventional agriculture mainly relies on the use of synthetic herbicides and intensive tillage. However, these measures that have indeed raised yields in the short run, have also triggered a series of negative ecological effects - herbicide resistance, soil degradation, biodiversity loss, and water contamination- are among these effects (Tataridas et al., 2022; Heap, 2014).

On the contrary, *regenerative* and *organic* agriculture illustrate two different paradigms which share common goals of restoring ecological processes and increasing the self-regulatory capacity of agroecosystems. Both systems highlight the inseparability of soil, plants, microbes, and the environment. Their final objective is not the control of weeds only, but the creation of resilient ecosystems where the natural control of weeds through ecological equilibrium rather than chemical eradication prevails (LaCanne & Lundgren, 2018; Lal, 2020).

The conventional logic of weed management has been eradication. However, the chemical approaches have their limitations, for instance, pollution of the environment and the problem of herbicide resistance, which have challenged weed ecology and management strategies to rethink. Adaptive management puts forward the aspects of learning and flexibility—being constantly involved in the monitoring of weed dynamics and being able to respond differentially to ecological feedback through adjusting practices (Liebman et al., 2018).

One of the main points of regenerative and organic systems is the understanding that healthy soils are the base of weed suppression. Soil organic matter, microbial diversity, and soil aggregate stability are some of the factors that affect the ability of crops to compete with weeds. Rich and diverse soil microbial communities can, for example, inhibit weed seed germination directly by allelochemical degradation or provision of resources for crop root growth which in turn takes away nutrients and space from the rhizosphere (Berg & Raaijmakers, 2018).

Besides that, biodiversity of both above and below ground can be considered a source of stability in agroecosystems. Crop diversification, polycultures, and agroforestry systems are some of the strategies that increase spatial and temporal heterogeneity thus prevent the supremacy of one particular weed species (Nichols et al., 2015). Under such conditions, weed control becomes the other side of the coin which is managing biodiversity and ecological design.

This paper aims to:

- First of all, it aims to identify the fundamental ecological and agronomic principles that lie behind regenerative and organic weed management system.
- Secondly, it aims to identify the biological, chemical, and physical mechanisms by which these systems bring about weed suppression.
- The third aim of the paper is to examine the innovations and technologies that are compatible with regenerative principles.
- Fourthly, the paper aims to perform a performance, advantages, and limitations comparison of regenerative and conventional weed management systems.

In essence, the research is to show that the sustainable control of weeds is not dependent on singe interventions but rather on the system-level integration of ecological processes. The

understanding of how regenerative and organic systems maintain the balance of weed populations will be a condition for productivity and ecological resilience, given the climate change and soil degradation challenges that global agriculture is facing.

PRINCIPLES OF REGENERATIVE AND ORGANIC AGRICULTURE

Regenerative and organic farming share one of their major beliefs - the belief that agricultural systems have to function in harmony with natural processes, not against them. Both systems put their main focus on sustaining soil health, biodiversity, nutrient cycles, and ecosystem resilience. But regenerative farming, by its very nature, moves beyond the organic certification standards as its ultimate goal is not only to restore but also to revitalize ecosystem functions, reverse soil degradation, and capture carbon from the atmosphere (Lal, 2020; Rhodes, 2017).

While organic farming would not allow the use of synthetic fertilizers and pesticides, regenerative farming would take more steps to restore biological processes, soil structure, and hydrological cycles. The core philosophy of both systems also emphasizes that weed management should result from ecological balance rather than be a separate technical intervention (Gattinger et al., 2012).

Soil Health as the Foundation of Weed Suppression

Soil health is the basis on which both regenerative and organic frameworks have been constructed. Healthy soils have better aggregate stability, higher microbial activity, and improved water-holding capacity—all of which are factors in weed–crop interactions.

Increasing the amount of organic matter in the soil also influences the weed seedbank through changing oxygen diffusion, temperature and microbial decomposition of dormant seeds (Kremer and Li, 2003).

By the same token, the use of microbial inoculants—such as Trichoderma, Azospirillum, and Bacillus species—strengthens plant–soil feedback loops and results in the formation of crop-associated rhizospheres which are the natural inhibitors of weed colonization. At the same time, these microbial communities that compete with weed rhizospheres for carbon substrates also release allelochemicals that facilitate the invasion of weed seedling growth (Berg & Raaijmakers, 2018).

Biodiversity and Ecological Balance

Biodiversity is the ecological insurance of an agricultural system that is sustainable. Species diversity both in the fields and in the surrounding areas in regenerative and organic systems creates the multilayered ecological interactions which are the regulators of weed populations. Through diverse crop rotations, mixed intercropping, and the use of cover crops, the dominance of one species of weeds is lessened because their life cycles are broken, and the niches available are limited (Teasdale et al., 1991).

For example, rotations alternating between cereals, legumes, and root crops bring about temporal variability in the availability of resources, thus making it hard for specialist weeds to adjust. In the same way, diversified landscapes with hedgerows, pollinator strips, and agroforestry buffers attract predatory insects and soil organisms that stabilizing the overall ecosystem and thus indirectly influencing weed suppression (Altieri, 1999).

Functional biodiversity, i.e., the range of ecological roles performed by organisms, also helps in the control of weeds. For instance, ground-cover plants are living mulches that, by shading the soil surface, reduce the light necessary for the germination of weed seeds (Leary and Defrank, 2000). In the same way, allelopathic species like rye (*Secale cereale*) and sorghum

(*Sorghum bicolor*) give off natural phytotoxins that discourage the growth of weeds, thus causing a friendly-to-the-environment herbicidal effect (Reberg-Horton et al., 2005).

Reduced Disturbance and Closed Nutrient Cycling

Minimal disturbance of the soil is one of the features that distinguish regenerative agriculture. Conventional tillage, though efficient in short-term weed removal, loosens the soil and oxidizes the organic carbon thereby increasing the turnover of weed seeds that are brought to the surface (Peigné et al., 2007). Systems that have reduced tillage and at the same time permanent soil cover are able to lessen the germination capacity of the weed seedbank while also improving soil biological activity (Liebman et al., 2018).

Closed nutrient cycling is another key principle of the regeneration that assures that fertility is kept inside through the means of composting, green manures, and livestock integration. Nutrient efficiency and microbial mediation greatly reduce the need for synthetic fertilizers, which if used can be a source of nitrophilous weeds that grow rapidly (Bond & Grundy, 2001).

Besides that, integrated grazing, mostly found in regenerative mixed farms, can recycle nutrients through the deposition of manure while at the same time physically controlling the weeds through selective browsing. The rotational grazing, if properly timed, can cut down on the biomass of species like *Conyza canadensis* and *Amaranthus retroflexus*, thus biologically controlling the weed dominance (Teague et al., 2011).

Holistic System Thinking

Regenerative and organic farming systems both require the use of a holistic approach in which each component of a farm i.e. soil, plants, animals, microbes, and human management are interconnected and self-regulating. Hence, weed control is not a separate aim but a consequence of the system's vigor. A well-organized system with active microbial life, diversified crops, and continuous ground cover naturally abates weed outbreaks (Gomiero et al., 2011).

Bàrberi (2002) observed, "Weeds are not only invaders of space but tellers of management imbalance." By recognizing this ecological signal, weed management becomes an act of ecosystem stewardship rather than mere suppression.

Table 1. Core Principles of Weed Management in Regenerative and Organic Systems

Principle	**Description**	**Ecological Function**	**Practical Example**
Soil Health Enhancement	Building soil organic matter and microbial diversity	Improves nutrient cycling and crop vigor	Composting, biochar use
Crop Diversification	Rotations, intercropping, and polyculture	Disrupts weed life cycles	Legume-cereal rotations
Minimal Disturbance	Reduced tillage and soil protection	Maintains soil structure and microbial balance	No-till with mulch
Biological Regulation	Use of microbes and allelopathic crops	Natural weed suppression	*Bacillus*-based bioinoculants
Continuous Cover	Living mulches or cover crops	Shade and moisture regulation	Clover or vetch cover crops

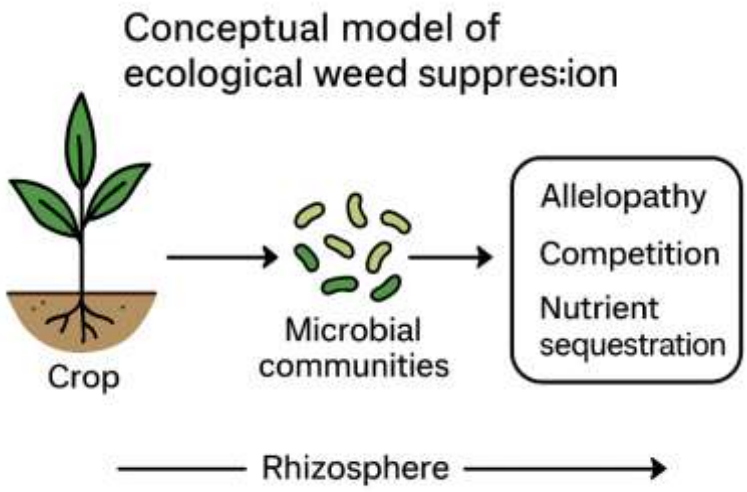

Figure 1. Conceptual model of ecological weed suppression in regenerative systems

CULTURAL AND MECHANICAL WEED CONTROL STRATEGIES

Cultural and mechanical methods are the main elements of weed management in regenerative and organic agriculture. Since synthetic herbicides are not allowed, farmers have to depend on preventive and integrative strategies for keeping the weed populations at a level that does not cause significant harm. These measures not only control the weeds but also improve soil fertility, biodiversity, and ecosystem resilience.

Crop Rotation and Temporal Diversification

One of the oldest and most powerful cultural methods for the reduction of weeds is crop rotation. By changing crops of different heights, nutrient requirements, and compositions of the canopy, the farmers can break the life cycle of the dominant weed species (Liebman & Dyck, 1993). As an illustration, the alternation of the fast-growing cereals with the slow-maturing legumes impedes the weeds which are adapted to one crop type from growing continuously.

The importance of temporal diversification cannot be overemphasized. The staggered planting dates, cover cropping during the fallow period, and intercropping result in the temporal gaps in the use of the resources, which are unfavorable to the germination of the weed seeds. Studies have revealed that rotations with the addition of leguminous cover crops can lower weed density up to 40% in comparison with monoculture systems (Teasdale et al., 1991).

Cover Crops and Living Mulches

Cover crops are living mulches and, thus, are able to offer both the physical and the chemical means for the suppression of weeds. The fast-growing species like rye (*Secale cereale*), oats (*Avena sativa*), and mustard (*Brassica juncea*) have the ability to form dense canopies that shade the weed seedlings which require light for their growth (Reberg-Horton et al., 2005).

The use of allelopathic cover crops is associated with the release of phytochemicals which hinder the germination of the weeds. To cite an example, rye manufactures benzoxazinoids while mustard releases glucosinolates and these are the substances that suppress the germination of the broadleaf weeds (Teasdale & Mohler, 2000). Besides that, cover crops are good for the soil as well because they enhance the soil structure and microbial activity thus making the soil more fertile for the crops and less friendly to the weeds.

Living mulches, such as low-growing legumes like white clover (*Trifolium repens*), provide a continuous cover of the ground that prevents the appearance of weeds during the whole growing season (Leary and Defrank, 2000). The use of a dual system of ecological and mechanical methods for the suppression of weeds can be achieved by the integration of cover crops and living mulches.

Mulching and Residue Management

Mulching is an additional cultural method that is effective. The purpose for which the organic mulches like straw, compost, and wood chips can be used is to create a physical barrier that obstructs light from coming in thus making it almost impossible for the weed seeds to germinate. Besides that, mulches regulate soil temperature and water content, thereby promoting crop growth and discouraging weed development.

Residue management is very much a part of mulching. After harvesting, the practice of leaving crop residues on the soil surface is beneficial both as a mulch and a source of organic matter. The residues decompose slowly, thus they contribute to soil carbon, and increase microbial activity, and hence, provide long-term weed suppression benefits (Bàrberi et al., 2005).

Mechanical Weed Control

Where there is a limitation on the use of chemicals, the mechanization of control measures becomes even more important. They are comprised of different activities such as hand weeding, hoeing, rotary cultivation, flame weeding, and inter-row cultivation. Currently, most regenerative systems are gradually adapting to the use of advanced precision machinery like robotic weeders fitted with sensors for the selective removal of weeds with minimal soil disturbance (Liu et al., 2021).

The mechanical weeding has to be done at the right time so that the target is the weeds before they set seeds. It has been found that very frequent or deep tillage can be the reasons for the disruption of soil structure and the stimulation of weed seed germination, thus the importance of mixing mechanical strategies with ecological knowledge cannot be overemphasized (Peigné et al., 2007).

Integration of Cultural and Mechanical Methods

The greatest success in weed management under regenerative and organic systems can be attributed to the cultural and mechanical approaches working together. An example can be given of cover crops that prevent early-season weed germination, mechanical cultivation that is used to target any survivors, and crop rotations which hinder weed populations from getting adapted.

The combination of winter rye cover crop, spring legumes, and maize rotation together with the shallow inter-row cultivation led to a reduction in weed biomass by 60% over three seasons as compared to continuous monoculture maize plots (Liebman et al., 2018). It is evident from this that integrated strategies have a synergistic effect in lowering the pressure of weeds while at the same time sustaining soil health.

Table 2. Cultural and Mechanical Weed Management Practices

Practice	Mechanism	Target Weeds	Benefits	Limitations
Crop Rotation	Life cycle disruption	Annual and perennial weeds	Reduces seedbank, improves soil	Requires planning, diversity
Cover Crops	Shade + allelopathy	Light-demanding weeds	Soil protection, microbial stimulation	Species-specific effects
Living Mulches	Continuous ground cover	Small-seeded weeds	Reduced germination, nitrogen fixation	Management complexity
Mulching	Physical barrier	Germinating seeds	Moisture retention, soil temperature	Labor-intensive
Mechanical Weeding	Seedling removal	All emerged weeds	Immediate reduction	Soil disturbance, labor

5. Soil Health, Microbiome, and Weed Suppression

Soil health is one of the main elements of regenerative and organic farming systems and it has a direct effect on the weed problem through the physical, chemical, and biological means. Soils that are in a good state with a high amount of organic matter, have good structural stability, and contain a diverse range of microorganisms provide crops with an edge over weeds, thus naturally making the latter's emergence and growth difficult (Gattinger et al., 2012).

Physical and Chemical Soil Properties

Weed seed germination and seedling vigor are affected by soil texture, structure, and organic matter content. So, according to Lal (2020), nicely aggregated soils improve water infiltration and retention, thus, crop roots are favored over weed seedlings. Organic matter increases cation exchange capacity, pH buffer, and nutrient provider by slow release, thus, enhancing crop resilience and competitiveness.

Residue retention and mulching also help to improve the soil microclimate by moderating temperature changes and lowering the light that reaches the soil surface - these are the factors that hinder the germination of photophilic weeds,. When combined, these physical and chemical properties set the baseline environment in which crops dominate and weeds are suppressed naturally.

Microbial Communities and Allelopathic Interactions

Soil microbial communities should be regarded as the main regulators of weed populations. Among beneficial bacteria and fungi, the genera Pseudomonas, Bacillus, and Trichoderma species, can inhibit weed seed germination and seedling growth by release secondary metabolites or by competition for nutrients (Berg & Raaijmakers, 2018; Kremer and Li, 2003).

Suppression of the rhizosphere is the result of interaction between crop roots and their microbiota that create a microenvironment unfavorable to weeds. Root exudates activate the beneficial microbes, which, in turn, suppress weeds through release of allelopathic compounds

or by induction of pathogen resistance in crops (Inderjit & Duke, 2003). This interaction is a major ecological feedback mechanism in regenerative systems.

Soil Fauna and Weed Regulation

he soil fauna that consists of earthworms, nematodes, and microarthropods, is capable of influencing weed populations indirectly through their effect on nutrient cycling and soil structure (Altieri & Nicholls, 2004). As an illustration, earthworms produce macropores that can be utilized by crop roots for penetration thus at the same time they change seed burial depth which has an impact on weed germination pattern. Furthermore, nematodes can also selectively consume weed seeds or seedlings and thus become one of the natural ways of weed suppression.

Cover Crops, Microbes, and Soil Health Synergies

Using cover crops leads to the increase of the diversity and the activity of the soil microbes. The leguminous cover crops like hairy vetch (Vicia villosa) gain the soil not only with nitrogen but also with rhizosphere microbial communities that suppress weeds (Teasdale et al., 1991). Non-leguminous allelopathic species, such as rye (Secale cereale), shed phytochemicals into the soil that stunt the germination of weeds and at the same time, beneficial microbes that support crop growth get activated.

Case Studies of Microbiome-Mediated Weed Suppression

The focus on controlling weeds by manipulating the microbiome is a research area that has brought a lot of attention in recent years. For instance, the results of Kaya et al. (2024) study demonstrated that inoculating rhizosphere bacteria could lead to a 30% reduction in broadleaf weed occurrence in a test field. In addition, the experiment with biochar amendment was effective in promoting microbial diversity that resulted in the weakening of the nitrophilous weeds' competitive ability (Major et al., 2010).

Table 3. Soil-Based Weed Suppression Mechanisms in Regenerative Systems

Mechanism	Description	Effect on Weeds	Agricultural Benefit
High Organic Matter	Improves structure, nutrients	Limits seedling establishment	Enhanced crop growth
Diverse Microbiome	Allelopathic or competitive microbes	Inhibits germination and growth	Reduced weed pressure
Cover Crop Integration	Provides root exudates and canopy cover	Physical + chemical suppression	Improved soil health
Minimal Tillage	Preserves microbial habitat	Alters seedbank dynamics	Stable weed populations
Soil Fauna Activity	Seed predation, nutrient cycling	Reduces weed vigor	Supports ecosystem resilience

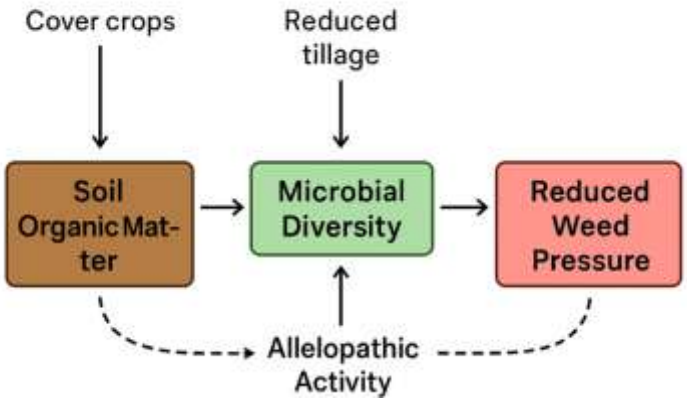

Figure 2. Interactions among soil health, microbial communities, and weeds.

INNOVATIVE AND TECHNOLOGICAL PRACTICES

Precision Mechanical Weeding

Generally, mechanical weeding using a hoe and inter-row cultivation is hard on human labor and may break up the soil structure. Precision mechanical weeding which involved the use of sensors and robots has been there to take away the drudgery of traditional mechanical weeding and also lessen the harm to soil that comes with these methods. What it does is that it recognizes the location of the weeds and eliminates them only (Liu et al., 2021).

The current methods employ cameras, LIDAR, or AI-based image recognition to pinpoint weed seedlings and direct robotic arms to remove them. By these means, the soil is hardly disturbed, the microbial habitats in the soil are preserved, and the labor costs are reduced. Field experiments have shown that precision weeding results in a 50-70% reduction in weed density as compared to traditional mechanical methods with soil structure and crop health being maintained.

Allelopathic Crop Breeding

Another future potential plan is the breeding of crops with allelopathic features. Allelopathic crops are one of the ways of decreasing the weed problem in which these crops release biochemical compounds that hinder the germination or growth of weeds. There are some plants like rye (Secale cereale), sorghum (Sorghum bicolor), and some varieties of rice that are highly allelopathic (Reberg-Horton et al., 2005; Kaya et al., 2024).

There are new breeding programs that work towards these traits being enhanced while yield and quality being not compromised. The reason is that, if there is an allelopathic trait, one can get a significant reduction of the weed seedbank through the combination of cover cropping and allelopathic cultivars-rooting natural herbicidal effect within an ecologically sustainable framework.

Microbiome Engineering

Among the rhizosphere microbiome, the ones that play a key role in weed regulation are those that can deal with the problem of microbial inoculants and soil amendments in the main one. There is a possibility of microbiome engineering with the aid of advanced inoculants and soil amendments-the deliberate installation and/or facilitation of beneficial microbial communities that lead to weed suppression (Berg & Raaijmakers, 2018).

As an example, biofertilizers with Bacillus subtilis or Pseudomonas fluorescens can be good for the crop, but should be avoided by weed seedlings. Soil amendment like biochar or compost not only change microbial activity but also it brings the community that produce allelopathic metabolites and nutrient competition that make the weeds vulnerable to such methods (Major et al., 2010).

Biochar and Soil Amendments

Addition of biochar not only is a good thing for the soil as it improves the soil structure and water retention but at the same time it relates with soil microbes and indirectly helps the soil microbes to suppress the weeds (Lehmann et al., 2011). By absorbing allelochemicals and giving shelters for the good microbes, biochar becomes more effective in rhizosphere-mediated weed suppression. When combined with organic mulches and compost, biochar can become an agent of not only weed management and fertility improvement but also carbon sequestration.

Digital Agriculture and Decision Support Tools

Digital means and precision agriculture software equip farmers with the ability to track down the changes in weed populations, forecast their coming up under the ground, and fine-tune their control measures in the best possible way. This becomes possible with the help of very fine instruments and accurate means such as satellite imaging, drone surveys, and soil sensors that reveal the short-term situations of weed hotspots, soil dryness, and nutrient status (Chandra et al., 2024). Decision support systems or DSS can make the best calls on when to sow, what cover crops to use, or what mechanization to apply, thus, giving room for the implementation of the regenerative practice of adaptive management.

Integration of Ecological and Technological Strategies

The mostly efficient modern practices are the ones that merge ecological rules with technical fixes. For instance, a system might consist of use of allelopathic cover crops together with precision robotic weeding which in turn is supported by microbial inoculants and biochar amendments. These combined tactics not only result in maximum weed suppression but also sustain or better soil health, biodiversity, and ecosystem resilience (Kaya et al., 2024).

In a multi-year field trial, regenerative maize systems incorporating allelopathic cover crops, reduced tillage, microbial inoculants, and AI-assisted mechanical weeding achieved a 65% reduction in weed biomass compared to conventional monoculture maize fields. Soil organic matter and microbial diversity also increased, demonstrating co-benefits for both crop productivity and ecological sustainability.

Table 4. Innovative and Technological Weed Management Practices

Practice	Mechanism	Benefits	Limitations
Precision robotic weeding	Targeted seedling removal	Reduces labor, preserves soil	High initial cost
Allelopathic crop breeding	Biochemical suppression	Natural weed control	Species-specific, research-dependent
Microbiome engineering	Beneficial microbes inhibit weeds	Enhances crop growth	Requires understanding of soil ecology
Biochar amendments	Improves microbial habitat and adsorbs toxins	Indirect weed suppression	Material availability, cost
Digital decision support	Remote sensing + AI	Predictive management, optimized interventions	Technical knowledge required

COMPARATIVE ANALYSIS: CONVENTIONAL VS. REGENERATIVE AGRICULTURE

Conventionally, weed management in agriculture mostly relied on the use of synthetic herbicides for achieving quick suppression, and the use of intensive tillage to further control the land. While such methods may provide short-term control and high crop yields, they often cause degradation of soil health, loss of biodiversity, and reduction of system resilience (Tataridas et al., 2022; Heap, 2014). On the other hand, regenerative and organic farming practices are built upon ecological principles and detailed strategies which primarily aim at the sustainable regulation of weeds rather than their killing.

Effectiveness in Weed Suppression

What conventional systems do best is to very quickly and drastically lessen weed biomass. They do this by making use of chemical herbicides which are very potent. But, as a result of the extensive use of these inputs, a wide range of herbicide resistance in major weed species, such as *Amaranthus palmeri*, *Conyza canadensis*, and *Lolium rigidum*, has occurred (Heap, 2014). Resistance is a factor that limits the effectiveness of the practice in the long run because it forces the users to increase the dose of chemicals or to create newer chemicals and, thus, a cycle of dependence is formed.

After an initial period where these systems live through the high weed pressure, regenerative and organic methods eventually reach the suppression of the latter to long-term through mechanisms of ecological regulation. Different means such as crop rotation, cover cropping, the use of allelopathic cultivars, and microbial inoculants hinder the dominance of any single weed species thus ensuring the fertility of soil and limiting the seedbank proliferation (Liebman et al., 2018; Berg & Raaijmakers, 2018).

Soil Health and Biodiversity Outcomes

Use of conventional methods for weed control is usually associated with the degradation of soil structure and microbial diversity. Frequent heavy tillage and herbicide application break microbial linkages, lower organic matter, and reduce habitat complexity for beneficial organisms (Gomiero et al., 2011). These impacts may indirectly lead to an increase in weed invasiveness through the weakening of crop competitiveness and the ecosystem's resilience.

On the other hand, regenerative farming practices improve soil health and biodiversity, which are essential components of natural weed control. The implementation of minimal tillage, use of organic fertilizers, and diverse cropping systems help to build healthy microbial communities and functional biodiversity that in turn create unfavorable conditions for the proliferation of aggressive weed species (LaCanne & Lundgren, 2018; Altieri, 1999). Consequently, regenerative systems may have slightly higher short-term weed presence but achieve more sustainable, resilient suppression over time.

Environmental and Socio-Economic Considerations

One of the major contributors of environmental degradation is agriculturally dependent on the use of herbicides. The system in question pollutes waterways, kills other plants, and emits greenhouse gases during chemical production and soil disturbance (Tataridas et al., 2022). In addition, resistance to herbicides raises production costs in the long run and limits the number of available management options.

Regenerative and organic farming practices, on the other hand, not only reduce the need for chemicals but also help in carbon sequestration through improved soil management and provide more ecosystem services such as pollination and natural pest control (Gattinger et al.,

2012). These systems may need to invest more labor at the beginning, but from a socio-economic perspective, they will eventually save money through soil fertility improvement and reduction of input use. Economic stability of the area is also enhanced by the local community and market which benefit from the availability of organic or sustainably grown products.

Integrated Perspective

Conventional and regenerative methods differ in lot of aspects, as shown in the table 5.

Table 5. Contrasts The Main Features Of Conventional And Regenerative Weed Management Strategies

Aspect	**Conventional Agriculture**	**Regenerative/Organic Agriculture**
Weed Control Method	Synthetic herbicides, intensive tillage	Crop rotation, cover crops, allelopathic cultivars, microbial inoculants, minimal tillage
Short-Term Effectiveness	High	Moderate
Long-Term Sustainability	Low	High
Soil Health	Degraded	Enhanced
Biodiversity	Reduced	Increased
Environmental Impact	Pollution, herbicide resistance	Reduced chemical inputs, ecosystem services
Labor Requirement	Low (mechanized/herbicide-based)	Moderate to high (cultural and mechanical integration)

To summarize, conventional systems might be able to deliver immediate weed control, but regenerative and organic systems eventually get there by using nature's cycles. The switch from eradication to ecological regulation essentially involves resilience, ecosystem health, and long-term productivity.

FUTURE PROSPECTS, POLICY IMPLICATIONS

The key to future weed management strategies in the context of regenerative and organic agriculture is ecological intensification working hand in hand with technological innovation. Main trends are:

- Enhanced Microbiome Manipulation: In-depth studies on microbiome will make it feasible to
- Allelopathic Crop Breeding: A natural, long-lasting mechanism is
- Precision and Digital Agriculture: Technologies such as sensor-equipped automated
- Agroecological Research and Farmer Knowledge Networks: Farmer

Policy

- Funds and perks: A financial support for
- Instruction and Extension

Support frameworks for policy play a vital role in facilitating

- Funds and Perks: Financial support through subsidies for cover crop
- Training and Extension Services: Conducting training on ecological
- Research Grants: Money invested in research on
- Market Access and Certification: Implementing

Policies that harmonize economic incentives with ecological

CONCLUSION

Proper weed management with sustainable methods including plant diseases control measures is highly needed in agriculture to maintain the balance of natural systems. Weed management in regenerative and organic agriculture represents a paradigm shift from eradication to ecological regulation. These systems achieve sustainable suppression of weeds while enhancing ecosystem services by focusing on soil health, biodiversity, crop competition, and microbial interactions. The key points listed below are the main takeaways from this study:

- Integration of Multiple Strategies: There is no method
- Soil and Microbial Health as Central Components: The
- Long-Term Sustainability: Despite the fact that initial
- Innovation and Technology: Precision
- Policy and Education: Assuming

Ultimately, sustainable weed practices in the context of regenerative and organic farming should not be understood as a complete eradication but rather as the maintenance of ecological balance. These agricultural systems, as research, technology, and policy frameworks are constantly changing, represent feasible resolutions to the interlinked problems of food production, soil conservation, and environmental stewardship.

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INTEGRATED POLICY APPROACHES FOR SUSTAINABLE WEED AND PLANT DISEASE MANAGEMENT

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ABSTRACT

Invasive plants and diseases of crops are the major biotic factors that decrease the productivity of global agriculture, challenge food security, and worsen farmer's living conditions. Weeds are competing with crops for light, nutrients, water, and space, while also being the sources of pests and pathogens. Plant diseases, which are caused by fungi, bacteria, viruses, and nematodes, thus, yield losses to the point where production costs rise. All these biotic stressors ganging together cause big economic and social problems, especially smallholder farming systems, where labor and money limitations make it difficult to adopt effective management practices. Environmentally friendly control methods, e.g., Integrated Weed Management (IWM) and Integrated Disease Management (IDM), advise on using ecological, cultural, mechanical, and biological methods for lessening the use of chemicals while at the same time not losing the crop yield level. The adoption of these eco-friendly activities is largely dependent on socioeconomic factors like financial capital, access to information, institutional support, risk perception, and gender equity. The proof of their benefits exists in different regions where the implementation of integrated strategies has not only lessened the weed and disease pressures but has also provided economic and environmental benefits over time. This work draws attention to the relationships between environment-friendly weed and disease control, their socio-economic factors, and the possibilities of their merging. By combining ecological, economic, and social aspects, a holistic framework can be a guide for policy-makers, extension agents, and farmers in the implementation of effective, fair, and sustainable crop health strategies. The essential points together with the examples given are put into the tables that feature the economic losses, management practices, and adoption constraints, thus, providing the agricultural stakeholders with the actionable insights.

Keywords: Sustainable agriculture, Weed management, Plant disease control, Socioeconomic factors, Integrated management, Smallholder farming

INTRODUCTION

Agriculture is considered a major system in stabilizing food security, creating job opportunities, and maintaining economic stability, especially in the regions of the Global South (Islam, 2025). Despite the sizeable contribution of crop productivity, it is constantly haunted by the presence of biotic stressors among which are weeds and plant diseases. Weeds, in their competition with crops, rob them of light, nutrients, water, and space, while at the same time they can also become the potential sources of pests and pathogens. The diseases of plants which originate from fungi, bacteria, viruses, nematodes, and other agents, have the ability to cause enormous yield reductions besides low product quality and the increase of production costs (Morgan et al., 2019).

The challenge of keeping productivity at a level while at the same time not causing harm to the environment can only be solved by the use of integrated and environmentally friendly weed and disease management strategies. Nevertheless, the decision to take on such a sustainable path does not depend solely on the technical side of things, but also on the labor availability, financial resources, risk perception, knowledge levels, institutional support, and equity considerations which are factors that belong to the socio-economic realm.

This paper is a discussion of the social and economic aspects related to the implementation of sustainable weed and disease management strategies and the emphasis is put on their intersections and mutual influences. The main points of the paper are arranged as follows: the economic and social impacts of the biotic stressors in agriculture, sustainable weed and disease management approaches and the barriers to their adoption, the integrated socioeconomic model, the case studies, and the policy recommendations.

ECONOMIC AND SOCIAL BURDENS OF WEEDS AND PLANT DISEASES

The presence of weeds is a major global economic burden in terms of both the direct loss of yields and the costs of management. As an example, it is estimated that weeds cost the grain and cotton sectors of Australia around 4.43 billion USD on a yearly basis. In the same way, in the United States and Canada uncontrolled weeds in corn and soybean fields can cause up to 50% yield loss, which is equivalent to approximately 43 billion USD annually (FAO, 2023). In the United Kingdom, herbicide-resistant "black grass" is the main factor behind losses that total £400 million each year and it is the major cause that decreases the wheat production by close to 800,000 tonnes (FAO, 2025). . In sub-Saharan Africa, parasitic weeds such as Striga are said to decrease cereal yields to the extent of 40-100%, and accordingly, the economic losses are estimated at 7 billion USD a year (FAO, 2003; Dechassa, 2021; Benjamin et al., 2023). Apart from the economic costs, weeds worsen the incidence of plant diseases as they are the alternate hosts for pathogens and pests.

Diseases of plants also lead to a hefty bill for the world economy. The losses of crops that are due to pests and pathogens are estimated to be 10-20% globally, which results in tens to hundreds of billions of dollars annually (Islam, 2025). Several factors such as intensified monocultures, climate change, and modern agricultural practices that are happening at the same time are said to be the major reasons for the exacerbation of plant disease outbreaks, thereby increasing the associated economic consequences (Gai and Wang, 2024s, 2024). Although biological control measures play a key role in the reduction of the demand for chemical interventions, there are some trade-offs with regard to their cost, labor, and ecological aspects (Fontaine et al., 2022. The integrated approaches that combine resistance breeding, cultural practices, and the use of chemicals in targeted and limited ways are very often the cheapest and most sustainable solutions.

In addition to the financial losses, weeds and diseases have detrimental impacts on the social side and the livelihoods of the people. In small-scale farming systems, labor that is used for manual weed control frequently takes up a major part of the household time and as a result, the time for other productive activities becomes limited. The spread of diseases may lead to the accumulation of debts, the lack of sufficient food, and migration. Also, there are gender disparities, for example, women who have to bear more than their share of the labor in weed management. On top of that, institutional weaknesses such as a low level of extension services, limited access to credit, and poorly developed plant health systems become additional barriers to the adoption of sustainable practices (Islam, 2025; Gai and Wang, 2024s, 2024) (Table 1).

Table 1. Summary of Selected Economic Cost Estimates for Weeds and Diseases

Context	**Cost / Yield Loss Estimate**	**Reference**
Australian grain & cotton	~ USD 4.43 billion annually	Global Agriculture, 2025
U.S. & Canada (corn, soybean uncontrolled)	USD 43 billion (50% yield loss)	ScienceDaily+1
UK (black grass resistance)	£400 million + 800,000 t wheat lost	Cambridge Institute for Sustainability Leadership
African Striga in cereals	~ USD 7 billion	Wikipedia, 2025
Global disease (10–20% losses)	Tens to hundreds of billions USD	Islam, 2025
Biocontrol trade-offs in disease	Varies; eco-economic analysis	Fontaine et al., 2022

SUSTAINABLE WEED MANAGEMENT: METHODS, SOCIOECONOMIC TRADE-OFFS, AND ADOPTION CONSTRAINTS

Environmentally friendly weed management stresses the necessity of ecological and integrated control of weeds as a way of limiting the use of chemicals and at the same time maintaining productivity. The methods involve the use of the following: crop rotation, cover cropping, intercropping, and changed sowing dates to suppress weed emergence. As for the mechanical means, there are precision tillage and robotic weeding, both of which are less labor-intensive and have a reduced use of herbicides. The biological control by using enemies or pathogens that are natural complements the mentioned practices and at the same time, mulching or soil management may be added to further restrict the germination of weeds. Integrated Weed Management (IWM) is the combination of these measures to have the best results both ecologically and economically (Travlos et al., 2017; Sims et al., 2018).

On the economic side, adopting environmentally friendly weed control measures brings both challenges and opportunities to light. While on the short term, the expenses might be higher due to the labor involvement, which is intensive, or the cost of the machinery in which one has to invest, on the long term, the gains will be the reduced herbicide spending, low resistance potential, better ecosystem services, and yield stabilization (Michalis et al., 2025). Nevertheless, what smallholder farmers might be lacking is the financial means and at the same time, they may not have enough risk buffers for them to undertake these practices without the

help of institutions. The success of the example is such as the integrated management of broomrape in Greek tomato fields, which has proven over the last five years that profitability can be increased by 25%, thus, pointing out the economic side of sustainable strategies as a potential (Michalis et al., 2025) (Table 2).

Table 2. Comparison of Conventional vs. Sustainable Weed Management

Factor	**Conventional (Herbicide-Based)**	**Sustainable (Integrated)**	**Reference**
Cost (Short-term)	Lower input/labor, recurring	May be higher (labor, equipment, training)	Monteiro & Santos, 2022; Jamakhandi et al., 2025
Environmental impact	High (pollution, resistance)	Lower, promotes soil & biodiversity	Monteiro & Santos, 2022
Labor requirement	Low	Medium to high	Sims et al., 2018
Knowledge requirement	Low to medium	High (site-specific management)	Jamakhandi et al., 2025
Adoption among smallholders	Widespread	Limited, depends on support	Sithole and Olorunfemi, 2024
Long-term sustainability	Low to moderate	High	Michalis et al., 2025

Two important factors, that is, socioeconomic and institutional, have a big impact on the adoption of the practice. When farmers get access to training, extension services, and localized information, they are more willing to carry out sustainable approaches. Also, being a member of cooperatives and farmer groups can be of great help in the sharing of knowledge and the implementation of collective action, thus, leading to the feasible realization of sustainable weed management. The gender inequalities, limited land tenure, and subsidized herbicides combined together in a bundle of problems that affect farmer's decision-making and may hinder involvement in the practice (Sims et al., 2018; Sithole and Olorunfemi, 2024).

SUSTAINABLE PLANT DISEASE MANAGEMENT: TECHNIQUES, SOCIOECONOMIC HURDLES, AND INTERACTIONS

Plant diseases, driven by fungal, bacterial, viral, and nematode pathogens, continue to cause significant Plant diseases, which are the main causes of crop losses globally, are mainly attributed to fungi, bacteria, viruses, and nematodes. The management of diseases is usually a major contributor via the use of chemical fungicides and pesticides that are a part of the usual management strategies. However, their sustainability is questioned due to the development of resistance, pollution, and effects on non-target organisms (Ma and Rahut, 2024). Sustainable Plant Disease Management (SPDM) achieves the goals of the integration of ecological, cultural, biological, and genetic methods with less use of chemicals and still maintaining the yield level.

SPDM methods mainly rely on the use of resistant varieties, disease control with the help of biologically-active agents, and cultural practices such as crop rotation, sanitation, and correct planting schedule (Hajji-Hedfi et al., 2024; Ma and Rahut, 2024). Integrated Disease Management (IDM) also incorporates these methods with minimal chemically guided

applications through monitoring and decision-making based on thresholds. However, the adoption of such measures is usually limited by monetary constraints, access to inputs, lack of training, and gender inequalities in land ownership and roles of labor, although they are technically feasible (Sithole and Olorunfemi, 2024; Sims et al., 2018).

Economic studies have revealed the potential long-term benefits of SPDM. As a result, blight-resistant potato varieties in East Africa led to a 50–80% reduction in fungicide application and a 15–25% increase in net incomes (Sithole and Olorunfemi, 2024). The introduction of biological control in India has led to a reduction in losses in the banana and vegetable sectors by 20–30%, along with the decrease in the costs of chemicals (Ali, 2012). In addition, farmer awareness through education and participatory methods has been found to reduce the transmission of diseases and the expenses related to it (Enyew and Gobie, 2025), 2018). The interaction between weed and disease management, e.g. the role of weeds as pathogen sources and competition of labor during peak seasons, further underlines the necessity of adopting integrated approaches (Table 3).

Table 3. Constraints to Sustainable Disease Management by Socioeconomic Factor

Factor	Constraint Example	Implication	Reference
Financial Capital	Cost of biocontrol agents or certified seeds	Limits adoption without subsidies	Ma and Rahut, 2024
Access to Information	Lack of extension services or digital tools	Reduces awareness	Sithole and Olorunfemi, 2024
Institutional Support	Weak plant health systems or seed distribution	Delays timely interventions	Junior et al., 2022
Risk Aversion	Perceived yield risk in moving away from chemicals	Preference for conventional methods	Sithole and Olorunfemi, 2024
Social Equity	Gendered labor roles and decision-making barriers	Unequal access to innovation	Sims et al., 2018

TOWARD AN INTEGRATED SOCIOECONOMIC FRAMEWORK FOR SUSTAINABLE WEED AND DISEASE MANAGEMENT

To understand and enhance management practices, a framework is needed that simultaneously integrates all the weed and disease issues in the farming systems. The shared drivers of unsustainable practices, such as labor shortages, market pressures, and reliance on chemical inputs, point to the potential benefits of a coordinated approach. From an environmental perspective, certain practices, such as crop rotation, not only reduce weed seed banks but also disease inoculum. The labor and money problems of smallholder systems highlight the need for intervention prioritization and the integration of policy incentives for both sectors (Sithole and Olorunfemi, 2024; Monteiro & Santos, 2022).

The integrated framework includes five aspects: ecological (weed-crop-pathogen interactions), economic (costs, returns, and risk perceptions), social (labor dynamics and gender roles), institutional (policies, subsidies, extension services), and technological (access to seeds, biocontrol, precision tools). The use of participatory methods such as Farmer Field Schools, community weed mapping, and village seed banks not only increases the adoption level but

also the local relevance of integrated management strategies (Erazo et al., 2024; Ali, 2012). Besides that, policy integration, digital decision-support tools, and eco-conditional subsidization are some of the other factors that facilitate efficient implementation (Ma and Rahut, 2024; Sithole and Olorunfemi, 2024).

Why Integration is Necessary

Integration is needed because most of the economic pressures that have caused the excessive use of chemical herbicides and pesticides for the treatment of plant diseases are almost always the same. These pressures are labor shortages, market demand for clean crops, and limited extension services. Besides that, some management practices have synergistic ecological effects, which influence both weeds and diseases. For instance, crop rotation can decrease both weed seed banks and disease inoculum (Monteiro & Santos, 2022). In smallholder systems, the labor and financial resources dedicated to disease management may lead to less attention being paid to weeds, and vice versa. Finally, governments and institutions can align subsidies, training, and research projects so that they address both weeds and diseases at the same time rather than treating them separately.

Components of an Integrated Socioeconomic Framework

Weed and disease management in an integrated manner could be based on five major interconnected dimensions, which are ecological, economic, social, institutional, and technological. The ecological dimension embraces the interactions between weed-crop-pathogen, the biodiversity, and the risk of resistance. The economic dimension addresses the evaluation of costs, returns, risk perception, and market access. The social aspects cover labor dynamics, gender roles, education, and community norms. Institutional elements cover policy, subsidies, extension services, and infrastructure. Last, but not least, technological aspects deal with the access to seeds, biocontrol agents, mechanical tools, and digital diagnostics. Integration of these dimensions allows the framework to understand the views of different stakeholders, i.e., farmers, policymakers, researchers, NGOs, and agribusiness actors (Sithole and Olorunfemi, 2024; Junior et al., 2022; Ma and Rahut, 2024).

Case For Participatory Approaches

The degree of implementation of sustainable practices in the management of weeds and diseases is higher if the farmers are engaged in the active formulation of strategies rather than simply receiving the advice. Participatory plant health management enables farmer-led experimentation and decision-making, thus resulting in a higher level of ownership and contextual relevance (Ali, 2012). A method like this is Farmer Field Schools, where through experiential learning, the integrated pest management practices can be more effectively adopted (Sims et al., 2018). Community weed mapping is a means of collective monitoring and planning of incoming invasive species, while village seed banks give the opportunity of distributing disease-resistant and weed-competitive varieties in the deprived areas (Hajji-Hedfi, et al., 2024; Erazo et al., 2025).

Integration in Policy and Practice

The integration of the management of diseases and weeds has been gradually reflected in agricultural policies. New modules referring to both weeds and diseases have enriched the FAO's Farmer Field Schools (FAO, 2023). Governments of countries, such as India and Kenya, are investing in digital decision-support tools that can assist smallholders in addressing several biotic stresses at a single platform (Sithole and Olorunfemi, 2024). Some European countries have subsidy programs that are being redesigned with "eco-conditionality," thus linking the

financial assistance for pesticides and herbicides to the implementation of sustainable integrated practices (Ma and Rahut, 2024). However, the extent of these measures is determined by consistent investment, institutional capacity, and long-term political will.

Barriers to Integration

Although there are benefits, a number of barriers prevent the realization of the integration in practice. Very often, research and extension services are arranged in silos, thus they focus on different pests or disciplines, e.g., pathology versus weed science. The financing that supports only one area at a time, e.g., pesticide reduction or seed system development, is also usually very specific. Furthermore, integrated strategies require local ecological and epidemiological knowledge, which is very often not available (Hajji-Hedfi, et al., 2024). Most development projects also have a short-term planning horizon, which is generally too short to see the full benefits of integrated systems, that usually take 3-5 years to show results (Junior et al., 2022).

Table 4. Key Integration Points Between Sustainable Weed and Disease Management

Integration Area	Example Practices	Benefit	Reference
Ecological	Crop rotation, cover cropping	Reduces weeds & disease inoculum	Travlos et al., 2017
Economic	Joint labor planning, cooperative input purchase	Cost-sharing & efficiency	Sims et al., 2018
Social	Farmer Field Schools, gender-inclusive training	Improved adoption & equity	Erazo et al., 2025
Technological	Digital monitoring, precision tools	Timely decision-making	Ma and Rahut, 2024
Policy	Eco-conditional subsidies, seed distribution programs	Incentivizes adoption	Sithole and Olorunfemi, 2024

REAL-WORLD APPLICATIONS OF SUSTAINABLE WEED AND DISEASE MANAGEMENT

Sustainable management of weeds and diseases has been adopted in various agricultural contexts, thus demonstrating the need for locally tailored, economically viable, and socially inclusive strategies. In certain parts of Greece, smallholder tomato farmers were heavily impacted by broomrape (Orobanche spp.), a parasitic weed that caused their yield to be drastically reduced. The traditional way of chemically controlling the problem seemed to be mostly unsuccessful and expensive. The use of Integrated Weed Management (IWM), which included such measures as postponing the time of sowing, using resistant hybrids, manual weeding, and targeted herbicide application, resulted in the reduction of yield losses by over 30%, herbicide use by 40%, and the increase of farm profitability by 25% within the period of five years (Michalis et al., 2025). The success depended on such factors as farmer training, subsidized access to improved seeds, and the close cooperation with agronomists, which demonstrated the vital role of economic and institutional support.

The potato farmers in Kenya and Uganda, both the countries in East Africa region, were plagued with the problem of late blight that kept re-occurring. However, they lacked, most of the times, the means to use effective fungicides and weather forecasting tools. The use of blight-

resistant potato varieties, thus, became a viable option and got support from NGOs and seed cooperatives, which facilitated a reduction in fungicide applications by 50–80% and also resulted in an increase of net income by 15–25% (Sithole and Olorunfemi, 2024). The adoption rate was higher for the members of the cooperative, but women farmers were left behind because of their limited access to seed capital and land, thus, pointing out the necessity of gender-sensitive interventions.

In Andhra Pradesh, India, the resistance to pesticides was widespread and became a major threat to cotton production. To counter the situation, Farmer Field Schools and IPM training were introduced, which promoted the use of methods such as crop rotation, pheromone traps, neem-based biopesticides, and manual weed removal. These steps led to a reduction in pesticide expenses by 40%, thus, yield variability was lowered, and collective action was also enhanced by means of group monitoring and input sharing, which in turn resulted in the sustainability and cost-effectiveness getting improved (Ali, 2012). The present instance serves to point out the worth of community-level approaches to solve the problem of economic and labor barriers.

The rice farmers in Vietnam are suffering more and more from the issue of weeds resistant to herbicides, as well as from fungal diseases, which are further aggravated by climate variability. To address these problems, climate-smart interventions such as laser land leveling, alternate wetting and drying (AWD), biological seed treatments, and farmer-led digital monitoring apps were introduced through public-private partnerships with the significant training and subsidies. The outcome was a 35% reduction in the use of chemicals, a 22% increase in water-use efficiency, and yield gains of 10–15%, thus, indicating the success of the combination of technology, institutional support, and local context (Ma and Rahut, 2024).

Across the diverse case studies presented, the key lessons that have been learned are in many respects similar. Success is facilitated by the access to training and advisory services, collective action through the cooperatives or shared monitoring, as well as by the financial and institutional support, gender-sensitive approaches and technologies that are suitable for local contexts (Michalis et al., 2025; Sithole and Olorunfemi, 2024; Ali, 2012; Ma and Rahut, 2024). Taken together, these examples demonstrate that sustainable weed and disease management can be realized if there are enabling environments, inclusive policies, and locally adapted solutions.

POLICY RECOMMENDATIONS AND FUTURE DIRECTIONS

The implementation of sustainable weed and plant disease management strategies is possible from a technical point of view and is frequently economically advantageous over the long term. Still, the adoption of such strategies is rarely talked about due to the existence of socio-economic, institutional, and informational barriers. To bring about large-scale changes, there is a need to change the orientation of agricultural policy, research priorities, and funding mechanisms (Sithole and Olorunfemi, 2024; Sims et al., 2018).

It is very important to revamp the extension services and farmer education, most notably via participatory models like Farmer Field Schools (FFS) that enable the farmers through experiential learning, combined with training the extension workers in integrated approaches and furnishing multilingual, digital advisory platforms to reach the less privileged groups, including women and youth (Ali, 2012; Ma and Rahut, 2024). There is also a need to reform subsidy and incentive structures since the present schemes are mostly designed in a way that benefits chemical inputs and disfavors Integrated Pest and Weed Management (IPM/IWM). The suggested measures are eco-conditional subsidies linked to the sustainable practices, input

vouchers for biological agents or resistant seeds, and performance-based incentives that reward a reduction in chemical use or an improvement in soil health, thus, easing the risk of adoption for farmers who are economically vulnerable (Junior et al., 2022).

It is also very important to provide the necessary conditions for innovation and local adaptation. The policies should encourage private-public investments in AI-powered disease and weed diagnostics that can be accessed via smartphones; subsidize startups and agritech companies to develop affordable precision instruments for smallholders; and, at the same time, create open-access repositories of localized weed and pathogen data to guide decision-making (Hajji-Hedfi, et al., 2024). All interventions must also focus on the social inclusion aspect and promote gender equity. They should focus on training women and other marginalized groups and providing them with seed distribution, promoting community-managed seed systems and including social impact assessments to ensure that everyone benefits (Sims et al., 2018).

Last but not least, a long-term policy vision should be in place that sees sustainable weed and disease management as an integral part of national agricultural and climate strategies. Among other things, this means the development of national action plans for Integrated Crop Health Management (ICHM), the creation of multi-stakeholder platforms involving farmers, scientists, NGOs, and private sector actors and support for research that is cross-sectoral and integrates weed science, plant pathology, social science, and economics. These steps together—covering extension, subsidy reform, innovation support, social inclusion, and strategic coordination—provide policymakers with the tools they need to build systems that are sustainable, fair, and resilient (Sithole and Olorunfemi, 2024; Ma and Rahut, 2024; Junior et al., 2022; Hajji-Hedfi, et al., 2024; Sims et al., 2018).

CONCLUSION

Managing sustainable weed and plant diseases is a must for the agricultural systems that want to remain resilient while meeting the ever-increasing demands for food security and environmental conservation worldwide. This review has highlighted the interconnected biological, economic, and social dimensions shaping the adoption and effectiveness of sustainable management strategies.

The growth of weeds and the occurrence of diseases in plants continue to be the major causes of significant losses of yields; however, the recourse to chemicals as a means of control, which has been the convential practice, is becoming less and less appropriate because of the various environmental, health, and resistance problems associated with it. Sustainable measures (integrated weed management, use of host resistance, biological control, and cultural practices) are viable alternatives to the traditional ones. Yet, the economic constraints, the limited access to knowledge and inputs, the institutional weaknesses, and the social inequalities negatively affect the widespread acceptance of these measures (Junior et al., 2022; Sims et al., 2018).

It is crucial to have an integrated framework that simultaneously addresses both weed and disease problems while taking into account socioeconomic realities. The implementation of such interventions as participatory, locally adapted, and supported by policies can bring about the desired effect, i.e., farmers will be able to adopt those practices which not only maintain their productivity but are also beneficial for the ecosystem (Ali, 2012; Hajji-Hedfi, et al., 2024).

Reforms in the fields of policy such as extension strengthening, subsidy realignment, technological innovation, and social inclusion are essential to be able to surmount the obstacles that hinder the adoption of inclusion and the scaling of impacts. Besides that, the firm political will and the coordination of the multi-stakeholder action that are required all the time will

facilitate the embedding of sustainable weed and disease management in the national and global agricultural strategies.

To sum up, the realization of sustainable crop health management goals goes beyond the technical challenges and rather represents a complex socio-ecological endeavor. Finding the link between science, policy, and farmer realities is the way to go if we are to have resilient and equitable food systems.

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ERZURUM İLİNDE KÜÇÜKBAŞ HAYVANCILIK İŞLETMELERİNİN SOSYO-DEMOGRAFİK ÖZELLİKLERİ VE BESLEME UYGULAMALARININ DEĞERLENDİRİLMESİ

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ÖZET

Bu araştırma, Erzurum iline bağlı Aziziye, Aşkale, Çat, Palandöken ve Yakutiye ilçelerinde faaliyet gösteren küçükbaş hayvancılık işletmelerinin demografik özellikleri ile besleme uygulamalarını belirlemek amacıyla yürütülmüştür. Çalışmanın materyalini 170 işletme sahibinden yüz yüze anket yoluyla elde edilen birincil veriler oluşturmuştur. Elde edilen bulgulara göre yetiştiricilerin %46.5'i 41–50 yaş aralığında, %31.8'i 31–40 yaş aralığında yer almakta olup, genç nüfusun sektöre katılımı sınırlıdır. İşletme sahiplerinin büyük çoğunluğu (%64.1) ortaokul ve lise mezunu, %28.8'i ilkokul mezunu, yalnızca %5.3'ü üniversite mezunudur. Deneyim süresi bakımından üreticilerin yaklaşık yarısı (%45.9) 11–20 yıllık yetiştiricilik deneyimine sahiptirler. Besleme alışkanlıklarına göre işletmelerin %69.2'si kaba yemi kendi üretimlerinden sağlamakta, %15.4'ü buna ilave olarak dışarıdan satın almaktadır. Kesif yem temininde ise %42.9'unun tamamen dışa bağımlı olduğu belirlenmiştir. Hayvanların %92.4 oranında günde iki kez yemlendiği, %67.1 oranında "önce kaba yem, sonra kesif yem" şeklinde bir yemleme sırasının tercih edildiği tespit edilmiştir. İşletmelerin %81.2'sinde yemleme işlemleri elle yapılmakta, yalnızca %18.8'inde otomatik yemlik kullanılmaktadır. Gebe hayvanlara ek yemleme uygulayanların oranı %90.6 iken, yem katkı maddesi (probiyotik vb.) kullananların oranı oldukça düşüktür (%2.4). Sonuç olarak, Erzurum'daki küçükbaş hayvancılık işletmeleri genel olarak geleneksel üretim yapısına sahip olup, eğitim düzeyinin ve mekanizasyonun artırılması sektörün verimliliği açısından önem arz etmektedir.

Anahtar Kelimeler: Erzurum, koyunculuk, besleme alışkanlıkları, sosyo-demografik yapı

EVALUATION OF SOCIO-DEMOGRAPHIC CHARACTERISTICS AND FEEDING PRACTICES OF SMALL RUMINANT FARMS IN ERZURUM PROVINCE

ABSTRACT

This study was conducted to determine the demographic characteristics and feeding practices of small ruminant farms operating in the Aziziye, Aşkale, Çat, Palandöken, and Yakutiye districts of Erzurum province. Primary data obtained through face-to-face surveys from 170 farm owners constituted the study material. According to the findings, 46.5% of the breeders were between the ages of 41 and 50, while 31.8% were between the ages of 31 and 40, indicating limited participation from the young population in the sector. The majority of farm owners (64.1%) were middle school or high school graduates, 28.8% were primary school graduates, and only 5.3% were university graduates. In terms of experience, approximately half of the producers (45.9%) had 11–20 years of farming experience. Based on feeding habits, 69.2% of the farms produced their own forage, while 15.4% purchased additional feed from abroad. For concentrate feed supply, 42.9% were determined to be completely dependent on external sources. It was determined that 92.4% of animals are fed twice a day, and 67.1% prefer a feeding order of "roughage first, then concentrate." Feeding is done manually in 81.2% of farms, and only 18.8% use automatic feeders. While 90.6% of farms use supplementary feeding for pregnant animals, the rate of those using feed additives (probiotics, etc.) is quite low (2.4%). Consequently, small livestock farms in Erzurum generally have a traditional production structure, and increasing education levels and mechanization is crucial for the sector's efficiency.

Keywords: Erzurum, sheep farming, feeding practices, socio-demographic structure

GİRİŞ

Tarım ve hayvancılık, ülkelerin ekonomik gelişmişlik düzeylerinden bağımsız olarak stratejik öneme sahip sektörler arasında yer almaktadır. Artan dünya nüfusu ve sağlıklı beslenme gereksinimi, hayvansal ürünlere olan talebi artırmakta ve hayvancılığı sürdürülebilir kalkınmanın temel bileşenlerinden biri haline getirmektedir. Küçükbaş hayvancılık, düşük işletme maliyeti, çok yönlü ürün verimi ve zorlu iklim koşullarına adaptasyon kabiliyeti sayesinde özellikle kırsal alanlarda önemli bir üretim kolu olarak öne çıkmaktadır. Koyunculuk, et, süt, deri ve yapağı üretimiyle ülke ekonomisine katkı sağlamakta, ayrıca kırsal istihdamın artırılması ve göçün önlenmesinde kritik bir rol üstlenmektedir (Kaymakçı, 2006; FAO, 2022).

Türkiye'de koyunculuk faaliyetleri çoğunlukla küçük ölçekli aile işletmeleri tarafından geleneksel yöntemlerle yürütülmekte, bu durum üretim verimliliğini sınırlamaktadır. Ancak 2010'lu yıllardan itibaren uygulanan destek politikaları sayesinde koyun varlığında yeniden artış eğilimi gözlenmektedir. Ülkenin coğrafi yapısı ve iklim özellikleri dikkate alındığında, özellikle Doğu Anadolu Bölgesinin koyunculuk açısından büyük bir potansiyele sahip olduğu görülmektedir (Yaprak ve Esenbuğa, 2024; TÜİK, 2024).

Bu kapsamda yürütülen bu araştırma, Erzurum iline bağlı Aziziye, Aşkale, Çat, Palandöken ve Yakutiye ilçelerinde faaliyet gösteren küçükbaş hayvancılık işletmelerinin demografik yapıları ile besleme uygulamalarını belirlemek amacıyla gerçekleştirilmiştir.

MATERYAL ve YÖNTEM

Bu araştırmanın verileri, Erzurum'un Aziziye, Aşkale, Yakutiye, Çat ve Palandöken ilçelerinde koyunculuk yapan 170 yetiştiriciyle yüz yüze gerçekleştirilen anketler aracılığıyla elde edilmiştir. İlçeler, koyun varlığı ve yetiştirme koşullarının bölgeyi temsil etmesi nedeniyle seçilmiştir. Örneklem, basit tesadüfi örnekleme yöntemiyle belirlenmiş olup, örnek büyüklüğü Yamane (2006) formülüne göre %3 hata payıyla hesaplanmıştır. Uç değer içeren birer anket, varyansı azaltmak amacıyla veri setinden çıkarılmıştır. Elde edilen veriler Microsoft SPSS 2020 programında değerlendirilmiştir.

TARTIŞMA ve SONUÇ

Erzurum'un Aziziye, Aşkale, Çat, Palandöken ve Yakutiye ilçelerinde küçükbaş hayvancılık yapan yetiştiricilerin yaş dağılımı incelendiğinde, üreticilerin büyük çoğunluğunun orta yaş grubunda yoğunlaştığı görülmektedir. Katılımcıların %46.5'i 41–50 yaş, %31.8'i 31–40 yaş aralığında yer almakta olup, genç yetiştirici oranı yalnızca %5.3'tür. Bu sonuç, genç nüfusun hayvancılığa yönelim göstermediğini ortaya koymaktadır. Türkiye'nin çeşitli bölgelerinde yapılan çalışmalarda da benzer bulgular elde edilmiştir. Güney Marmara Bölgesi'nde yetiştirici yaş ortalaması 41.5–44.9 (Çetin ve Koyuncu, 2000), Van'da 46 (Şahin ve Yıldırım, 2002), Doğu Anadolu Bölgesi'nde 48 (Şahin ve Yılmaz, 2008) ve Kastamonu'da 49.3 (Bilginturan ve Ayhan, 2009) yaş olarak bildirilmiştir. Bu veriler, Erzurum'daki yaş dağılımının Türkiye genelindeki eğilimlerle uyumlu olduğunu göstermektedir.

Tablo 1. Yetiştiricilerin Genel Özellikleri

Değişkenler	Sayı (adet)	Yüzde (%)
Yaş		
18-30	9	5.3
31-40	54	31.8
41-50	79	46.5
51-60	25	14.7
61 ve üzeri	3	1.8
İşletmedeki birey sayısı		
1-3	120	70.6
4-6	48	28.2
7 ve üzeri	2	1.2
Eğitim düzeyi		
Okuma-Yazma bilmiyor	1	0.6
Okur-Yazar	2	1.2
İlkokul mezunu	49	28.8
Ortaokul mezunu	58	34.1
Lise mezunu	51	30.0
Üniversite mezunu	9	5.3
Kaç yıldır bu işi yapıyorsunuz?		
1-10	73	42.9
11-20	78	45.9
21-30	11	6.5
30-45	6	3.5
46 ve üzeri	2	1.2

Aile birey sayıları bakımından, Erzurum'daki işletmelerin %70.6'sının 1–3 kişilik ailelerden oluştuğu belirlenmiştir. Erzincan'da yapılan bir araştırmada 3–5 kişilik aile oranı %62.0, 6–8 kişilik aile oranı %27.7 olarak bildirilmiş olup (Özsağlıcak, 2019), birçok bölgede hayvancılıkla uğraşan ailelerin 4–6 kişiden oluştuğu görülmektedir. Buna göre Erzurum'daki küçük aile yapısı, işletmelerin daha küçük ölçekli ve sınırlı işgücüne dayalı olduğunu düşündürmektedir.

Eğitim düzeyi sonuçlarına göre yetiştiricilerin %34.1'i ortaokul, %30'u lise ve %28.8'i ilkokul mezunudur. Üniversite mezunu oranı yalnızca %5.3'tür. Diğer araştırmalar da bu bulguyu desteklemektedir. Kaylan (2019), yetiştiricilerin büyük kısmının ortaokul ve lise mezunu olduğunu bildirmiştir. Şanlıurfa'da yapılan çalışmada da yetiştiricilerin %31.71'inin ilkokul mezunu olduğu ifade edilmiştir (Mundan ve ark., 2018). Bu bulgular, kırsal bölgelerde eğitim düzeyinin genel olarak düşük olduğunu göstermektedir.

Tablo 2. Hayvan Besleme ve Yemleme ile İlgili Genel Bilgiler

Değişkenler	Sayı (adet)	Yüzde (%)
Kaba yemi nereden temin ediyorsunuz?		
Kendi işletmemden	118	69.2
Kiralık arazilerden	2	1.2
Dışarıdan satın alarak	24	14.1
Kendi üretimine ilave olarak dışarıdan satın alıyor	26	15.4
Diğer	0	0
Kesif yemi nereden temin ediyorsunuz?		
Kendi işletmesinde üretiyor	27	15.9
Dışarıdan satın alıyor	73	42.9
Kendi üretimine ilave olarak dışarıdan satın alıyor	69	40.6
Diğer	1	0.6
Gebe hayvanlara ek yemleme yapıyor musunuz?		
Evet yapıyorum	154	90.6
Hayır yapmıyorum	16	9.4
İşletmenizde hayvanları günlük yemleme sıklığınız nedir?		
1 defa	2	1.2
2 defa	157	92.4
3 defa	0	0
3'den fazla	1	0.6
Serbest yemleme	10	5.9
Hayvanları yemleme yönteminiz nasıldır?		
Önce kaba yem sonra kesif yem	114	67.1
Önce kesif yem sonra kaba yem	1	0.6
Birlikte (karışık)	55	32.4
Diğer	0	0
Hayvanlara yem dağıtımını nasıl yapıyorsunuz?		
Elle	138	81.2
Traktörle	0	0
Otomotik yemliklerle	32	18.8
Diğer	0	0
Tuz veya yalama taşı kullanıyor musunuz?		
Evet	166	97.6
Hayır	4	2.4
Hayvan beslemede yem katkı maddeleri (probiyotik vs.) kullanıyor musunuz?		
Evet	4	2.4
Hayır	166	97.6
Kuzular için kesif yem kullanıyor musunuz?		
Evet	137	80.5
Hayır	33	19.5
Kuzulara doğumdan ne kadar sonra ek yem (kaba/kesif) vermeye başlıyorsunuz?		
1.haftadan sonra	2	1.2
2.haftadan sonra	48	28.2
3.haftadan sonra	102	60.0
Sütten kesildikten sonra	9	5.3

Mesleki deneyim açısından değerlendirildiğinde, Erzurum'daki yetiştiricilerin %45.9'unun 11–20 yıl, %42.9'unun 1–10 yıl deneyime sahip oldukları görülmektedir. Uzun yıllar yetiştiricilik yapanların oranı düşük olmakla birlikte, sektörde hem yeni hem de orta düzey deneyime sahip üreticilerin yoğun olduğu anlaşılmaktadır. Erzincan'da yapılan araştırmada ise 31–45 yıl arasında deneyimi olanların oranı %28.3 ve 45 yıl üzeri deneyimli olanların oranı %29.6 olarak bildirilmiştir (Özsağlıcak, 2019). Bu karşılaştırma Erzurum'daki yetiştiricilerin

daha genç bir deneyim profiline sahip olduklarını göstermektedir. Genel olarak, Erzurum'daki küçükbaş hayvancılık işletmeleri orta yaş grubunda yoğunlaşan, eğitim düzeyi ilk ve ortaöğretim ağırlıklı olan, küçük aile yapısına sahip ve 10 yılın üzerinde deneyime sahip yetiştiriciler tarafından yürütülmektedir. Bulgular, Türkiye'nin farklı bölgelerindeki çalışmalarla büyük ölçüde paralellik göstermektedir.

Erzurum'un Aziziye, Aşkale, Çat, Palandöken ve Yakutiye ilçelerinde küçükbaş hayvancılık yapan işletmelerin besleme alışkanlıklarına ilişkin veriler incelendiğinde, üreticilerin büyük çoğunluğunun kaba yemi (%69.2) kendi işletmesinde ürettiği, kesif yemi ise büyük oranda dışarıdan temin ettiği (%42.9) veya kendi üretimine ek olarak satın aldığı (%40.6) görülmektedir. Bu durum, bölgedeki işletmelerin kaba yem açısından daha çok kendi kaynaklarına dayandığını, ancak kesif yem temininde dışa bağımlılığın yüksek olduğunu göstermektedir. Ekonomik koşullar, yem fiyatlarındaki artış ve üretim maliyetleri bu tercihte etkili olabilmektedir. Burdur ilindeki koyun yetiştiricilerinin %53.3 oranında yemi kendilerinin ürettiğini, %43.1 oranla da yem fabrikalarından satın aldıkları bildirilmiştir (Bilginturan ve Ayhan, 2009). Bu oranlar Ankara ili Çamlıdere ilçesindeki koyun yetiştiricileri için aynı sırayla % 36 ve % 64 olarak bildirilmiştir (Taşkesti, 2021)

Gebe hayvanlara ek yemleme, işletmelerin %90.6'sında uygulanmaktadır. Bu yüksek oran, yetiştiricilerin gebelik döneminde enerji ve protein ihtiyacının arttığı bilincine sahip olduklarını ve flushing uygulamasının döl verimi üzerindeki olumlu etkilerini bildiklerini ortaya koymaktadır. Gezer (2010), Sivas'taki işletmelerde koçlara ek yemleme oranının %98.33 olduğunu belirtmiş; Erzurum verileri de benzer şekilde üreticilerin ek yemleme konusunda oldukça bilinçli olduğunu göstermektedir.

Yemleme sıklığı, işletmelerin %92.4'ünde günde iki öğün şeklindedir. Bu oran, ülke genelinde yaygın olan alışkanlıklarla uyumludur. Akkuş (2009), işletmelerin %74.8'inin günde iki kez yemleme yapıldığını bildirmiştir. Erzurum'daki daha yüksek oran, yetiştiricilerin düzenli yemleme uygulamalarına önem verdiğini göstermektedir. Günlük bir öğün besleme yapan işletme oranı ise oldukça düşüktür (%1,2).

Yemleme yöntemi incelendiğinde, işletmelerin %67.1'i önce kaba, sonra kesif yem verdiğini; %32.4'ü ise karışık yemleme yaptığını ifade etmişlerdir. Bu bulgu, bölgede geleneksel besleme alışkanlıklarının hâlâ yaygın olduğunu göstermektedir. Kesif yemin önce verildiği işletme oranı ise oldukça düşüktür (%0.6).

Yemin dağıtım şekli açısından üreticilerin %81.2'si hayvanları elle yemlemekte, yalnızca %18.8'i otomatik yemlik kullanmaktadır. Traktörle yemleme yapan işletme bulunmamaktadır. Bu sonuç, Erzurum'daki işletmelerde mekanizasyon seviyesinin düşük olduğunu göstermektedir. Ekonomik kısıtlar, küçük ölçekli işletme yapısı ve geleneksel üretim alışkanlıkları otomasyonun sınırlı kalmasına neden olmaktadır.

Mineral madde desteği açısından işletmelerin %97.6'sının tuz veya yalama taşı kullandığı belirlenmiştir. Bu oran oldukça yüksektir ve yetiştiricilerin mineral gereksinimlerinin farkında olduklarını göstermektedir. Ancak yem katkı maddesi (probiyotik, vitamin-mineral premiksler vb.) kullananların oranı yalnızca %2.4'tür. Bu sonuç, üreticilerin katkı maddelerine erişim sıkıntısı yaşadıklarını veya bu ürünlerin faydaları konusunda yeterli bilgiye sahip olmadıklarını düşündürmektedir.

Kuzuların beslenmesi değerlendirildiğinde, işletmelerin %80.5'inin sütten kesim öncesinde kesif yem kullandığı görülmektedir. Bu oran, erken dönem ruminant gelişimi açısından olumlu bir uygulamadır. Kuzulara ek yem başlanma zamanı incelendiğinde, yetiştiricilerin %60'ı 3. haftada, %28.2'si ise 2. haftada ek yem vermeye başlamaktadır. Bu değerler literatürle

uyumludur. Kırıkkale'de kuzulara ortalama 19. günde yem verildiği (Bostancı, 2006), Doğu Anadolu'da sütten kesimin 3.92 ayda gerçekleştiği (Karaca ve ark., 1993) bildirilmiştir. Erzurum'da sütten kesim sonrası ek yem kullanım oranının (%5.3) düşük olması, çoğu işletmede ek yemlemenin erken başlamasıyla ilişkilendirilebilir.

Genel olarak değerlendirildiğinde, Erzurum'daki küçükbaş hayvancılık işletmelerinin besleme uygulamalarının geleneksel yöntemlerle yürütüldüğü, kaba yem üretiminde işletmelerin kendi kaynaklarına güvendikleri, kesif yem temininde ise dışa bağımlılığın yüksek olduğu görülmektedir. Gebe hayvanlara ek yemleme ve kuzulara erken dönem ek yem verilmesi yaygın olup, bu durum üreticilerin verim ve döl verimi konularındaki farkındalığını yansıtmaktadır. Ancak otomasyonun düşük olması ve yem katkı maddeleri kullanımının sınırlı olması, işletmelerin modern besleme tekniklerine geçiş konusunda desteklenmesi gerektiğini göstermektedir.

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KARS İLİNDE SÜT SIĞIRCILIĞI İŞLETMELERİNİN MEVCUT DURUMU VE GELİŞME OLANAKLARI

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ÖZET

Bu çalışma, Kars ilinde faaliyet gösteren büyükbaş hayvancılık işletmelerinin yetiştirici profillerini ve hayvan varlıklarını belirlemek amacıyla yürütülmüştür. Anket yöntemiyle elde edilen veriler, bölgedeki süt sığırcılığı sektörünün sosyo-ekonomik ve üretimsel dinamiklerini ortaya koymaktadır. Katılımcıların büyük çoğunluğu (%80'den fazlası) 26–55 yaş aralığında yer almaktadır. Bu durum yetiştiricilerin deneyimli olduklarını ancak yaş ortalaması yüksek bir yapıya sahip olduğunu göstermektedir. Eğitim düzeyine bakıldığında, yetiştiricilerin %68,8'inin ilkokul mezunu olduğu, üniversite mezunu üretici bulunmadığı belirlenmiştir. Bu durum, bölgedeki hayvancılık faaliyetlerinde modern tekniklerin benimsenmesini sınırlayan önemli bir faktör olarak değerlendirilmektedir. İşletmelerin %64.4'ü 11–30 baş büyükbaş hayvana sahip olup, işletme ölçeklerinin çoğunlukla küçük ve orta düzeyde olduğu görülmüştür. Hayvan ırkı tercihinde melez ırklar (%92.2) belirgin bir üstünlük göstermiştir; bu da yüksek verim ve bölgesel adaptasyonun birlikte hedeflendiğini göstermektedir. Buna karşılık yerli ırk oranının düşük olması, genetik çeşitlilik açısından risk oluşturmaktadır. Araştırmada ayrıca, işletmelerin yarısından fazlasında düve (%52.9) ve dana (%51.2) bulunmadığı belirlenmiştir. Bu durum dış kaynaklı hayvan teminine ve dolayısıyla hastalık risklerine yol açabileceği endişesini ortaya çıkarmaktadır. Sonuç olarak, Kars'taki süt sığırcılığı işletmeleri aile işletmesi niteliğinde olup, deneyimli fakat düşük eğitim düzeyine sahip üreticiler tarafından yürütülmektedir. Çalışma, sürdürülebilir üretim için damızlık yetiştiriciliğinin teşviki, yerli ırkların korunması, eğitim faaliyetlerinin artırılması ve örgütlenmenin güçlendirilmesi gerektiğini ortaya koymaktadır.

Anahtar kelimeler: Kars ili, Süt sığırcılığı, İşletme yapısı, Yetiştirici profili

CURRENT STATUS AND DEVELOPMENT OPPORTUNITIES OF DAIRY CATTLE ENTERPRISES IN KARS PROVINCE

ABSTRACT

This study was conducted to determine the breeder profiles and animal assets of cattle farms operating in Kars province. Data obtained through a survey reveals the socio-economic and production dynamics of the dairy cattle sector in the region. The vast majority of participants (over 80%) are between the ages of 26 and 55. This indicates that while these breeders are experienced, their average age is high. Regarding education level, 68.8% of breeders are primary school graduates, with no university graduates. This is considered a significant factor limiting the adoption of modern techniques in livestock farming activities in the region. 64.4% of farms own 11-30 head of cattle, and the farm size is mostly small to medium. In terms of breed selection, hybrid breeds (92.2%) showed a significant advantage, indicating a combined goal of high productivity and regional adaptation. Conversely, the low proportion of native breeds poses a risk to genetic diversity. The study also found that more than half of the farms lacked heifers (52.9%) and calves (51.2%). This raises concerns about the potential for outsourcing of livestock, which could lead to disease risks. Consequently, dairy farms in Kars are family-run, run by experienced but low-educated producers. The study demonstrates that sustainable production requires encouraging breeding stock, protecting local breeds, increasing training, and strengthening organizational structures.

Keywords: Kars Province, Dairy Farming, Farm Structure, Farmer Profile

GİRİŞ

Kars ili, sahip olduğu geniş mera ve çayır alanları sayesinde Türkiye'nin önde gelen hayvancılık merkezlerinden biri olarak öne çıkmaktadır. Bölgedeki meralar buğdaygil (%55–65), baklagil (%23–30) ve diğer bitki türleri (%13–15) bileşiminden oluşmakta olup, bu ekolojik yapı özellikle büyükbaş hayvancılık için son derece uygun koşullar sağlamaktadır. Doğu Anadolu Bölgesi genelinde olduğu gibi Kars'ta da büyükbaş hayvancılık, kırsal nüfusun temel geçim kaynağı ve ekonomik faaliyetin ana kolunu oluşturmaktadır. Sanayi ve hizmet sektörlerinin yeterince gelişmemiş olması ve karasal iklimin bitkisel üretimi sınırlaması, hayvancılığın bölge ekonomisindeki önemini artıran faktörlerdir (SERKA, 2017). TÜİK (2024) verilerine göre, Kars ilinde toplam 604.208 baş sığır bulunmaktadır. 2015–2022 yılları arasında sığır varlığı sürekli artış gösterirken, 2023 yılından itibaren azalma eğilimine girmiştir. Bu süreçte melez ve kültür ırkı sığırların oranı artarken, yerli ırkların sayısında belirgin bir düşüş gözlenmiştir. Yerli ırklar (Yerli Kara, Doğu Anadolu Kırmızısı) iklim koşullarına yüksek uyum gösterse de, et ve süt verimleri ithal ırklara kıyasla düşüktür (Akkaya, 2015). Bölgede kültür ırklarının yaygınlaşması, et verimini artırmakla birlikte yerli genetik kaynakların sürdürülebilirliği açısından risk oluşturmaktadır (Turhan, 2010).

Türkiye genelinde yapılan benzer araştırmalar da kırsal hayvancılık yapısının çoğunlukla küçük ölçekli ve geleneksel nitelikte olduğunu göstermektedir. Erzurum'da Çapadağ (2016), işletme sahiplerinin ortalama yaşını 47, hayvancılıkla uğraşma süresini ise 27 yıl olarak belirlemiş; yetiştiricilerin çoğunun ilkokul mezunu olduğunu ve bağlı duraklı ahır sistemi kullandığını rapor etmiştir. Iğdır'da Kaylan vd. (2019), işletmelerin %84,6'sının hayvan sayısını artırmayı hedeflediğini, üreticilerin ise modernizasyon konusunda teşvik beklediklerini belirtmiştir. Çankırı'da Kaba ve Çanakcı (2020), modern işletmelerin mekanizasyon düzeyinin geleneksel işletmelere göre çok daha yüksek olduğunu; Ankara Polatlı'da Koçak (2020) ise barınaklarda refah koşullarının yetersiz, kayıt sistemlerinin ise zayıf olduğunu saptamıştır. Kars ve Ardahan illerinde yapılan çalışmada (Güven, 2021), sığır yetiştiriciliğinin küçük ölçekli aile işletmeciliği şeklinde yürütüldüğü, yerli ırkların hâlen yaygın olduğu ve üreticilerin önemli bir bölümünün sosyal güvenceden yoksun bulunduğu bildirilmiştir. Erzurum Pasinler'de Aydın (2022), üreticilerin sigorta ödeme istekliliğinin sosyal güvenlik ve gelir düzeyine bağlı olduğunu belirlemiş; Kaygısız vd. (2022) ise sigorta sisteminin yüksek poliçe bedelleri ve bilgi eksikliği nedeniyle yaygınlaşamadığını vurgulamıştır. Kars'ta kooperatifçiliğin gelişmemiş olması, üreticilerin pazarlama süreçlerinde aracı bağımlılığını artırmakta, yem fiyatlarındaki dalgalanmalar ise üretim maliyetlerini yükseltmektedir. Bu durum, küçük ölçekli işletmelerin sürdürülebilirliğini tehdit etmekte ve kırsal göçü hızlandırmaktadır (Tutar vd., 2012; Anonim, 2019). Tarım ve Orman Bakanlığı ile TKDK tarafından yürütülen destek programları, modernizasyonu teşvik etse de bu desteklerden en çok büyük ölçekli işletmeler yararlanabilmektedir (Çelik, 2019).

Bu çalışmada, Kars ilinde süt sığırcılığı yapan işletmelerin mevcut yapısal özelliklerini, yetiştirici profillerini, ırk tercihlerini ve üretim eğilimlerini belirlemek; bölgenin hayvancılık potansiyelini ve gelişim olanaklarını ortaya koymak büyük önem taşımaktadır. Bu araştırma, bölgesel üretim yapısının bilimsel olarak değerlendirilmesiyle, Kars'ın sürdürülebilir hayvancılık politikalarına yönelik stratejik veri sağlamayı amaçlamaktadır.

MATERYAL VE YÖNTEM

Bu araştırmanın materyalini, Kars ilinde büyükbaş hayvancılık faaliyeti yürüten işletmelerin yapısal özelliklerini, üretim koşullarını ve karşılaştıkları temel sorunları belirlemeye yönelik gerçekleştirilen anket çalışmasından elde edilen birincil veriler oluşturmaktadır. Veri toplama süreci, ilin hayvancılık açısından öne çıkan iki önemli bölgesi olan Sarıkamış ve Merkez ilçelerine bağlı kırsal yerleşim birimlerinde yürütülmüştür. Toplam 244 üretici ile yüz yüze görüşmeler yapılmıştır. Örnekleme yapılacak işletme sayısının belirlenmesinde bazı istatistiksel verilere ulaşılamamış; bu nedenle örneklem seçiminde Basit Tesadüfi Örnekleme Yöntemi tercih edilmiştir (Yamane, 2006). Anket formu, üreticilerin sosyo-demografik özellikleri, işletme büyüklüğü, hayvan varlığı, ırk tercihleri, üretim hedefleri ve karşılaşılan temel sorunlara ilişkin sorulardan oluşmuştur. Görüşmeler, her üreticiyle bire bir gerçekleştirilmiş, sorular gerektiğinde açıklanarak yanıtların doğruluğu ve güvenilirliği artırılmıştır. Toplanan veriler MS Excel programı aracılığıyla düzenlenmiş, ardından SPSS 25.0 (2020) paket programında analiz edilmiştir (SPSS, 2020).

TARTIŞMA VE SONUÇ

Kars ilinde büyükbaş hayvancılık işletmeleri üzerine yürütülen bu araştırmada elde edilen demografik bulgular, hem bölgenin üretim yapısına ışık tutmakta hem de literatürde farklı bölgelerde yapılmış benzer çalışmalarla karşılaştırıldığında Türkiye'nin kırsal hayvancılık yapısına ilişkin önemli benzerlikler ortaya koymaktadır. Çalışmanın sonuçları, büyükbaş hayvancılığın ağırlıklı olarak orta yaş ve üzerindeki, eğitim seviyesi düşük ancak yüksek tecrübeye sahip üreticiler tarafından yürütülen bir faaliyet olduğunu göstermektedir. Öncelikle, üreticilerin yaş profili incelendiğinde katılımcıların büyük çoğunluğunun 36–55 yaş aralığında yoğunlaştığı (%53.3), genç nüfusun (18–25 yaş) sektörde oldukça düşük oranla temsil edildiği (%8.6) belirlenmiştir. Bu durum, gençlerin hayvancılığa ilgisinin düşük olduğunu ve üretici nüfusunun giderek yaşlandığını göstermektedir. Benzer şekilde Tatar'ın (2019) İzmir Ödemiş'te yürüttüğü çalışmada yetiştiricilerin çoğunluğunun 36–55 yaş aralığında yer aldığı bildirilmiştir. Farklı illerde yapılan araştırmaların da bu bulguları desteklediği görülmektedir. Kocaman (2014) ve Sevimli (2020)'e göre Türkiye'de hayvancılık faaliyeti ağırlıkla orta yaş ve üzeri yetiştiriciler tarafından yürütülmektedir. Tüm bu çalışmalar birlikte değerlendirildiğinde, Türkiye genelinde büyükbaş hayvancılığın kuşaklar arası aktarımında bir zayıflama olduğu ve gençlerin sektöre dahil olma eğilimlerinin düşük kaldığı anlaşılmaktadır.

Araştırmada işletmedeki birey sayısına ilişkin bulgular da literatürle uyumludur. Katılımcıların %43.9'unun 4–6 kişilik, %30.3'ünün ise 7 kişi ve üzeri bireyden oluşan işletmelere sahip olması, bölgedeki hayvancılık işletmelerinin çoğunlukla aile iş gücüne dayalı geleneksel işletmeler olduğunu göstermektedir. Tatar'ın (2019) Ödemiş ilçesinde yürüttüğü çalışmada toplam çalışanların %66.7'sinin 4–6 kişiden oluştuğunun bildirilmesi, elde edilen bulguların Türkiye'nin farklı bölgeleriyle tutarlı olduğunu göstermektedir. Benzer şekilde Özsağlıcak (2019)'da birçok hayvancılık işletmesinde iş gücünün temel olarak aile bireylerinden oluştuğunu ortaya koymuştur. Bu durum, hayvancılıkta profesyonel iş gücünün sınırlı, aile yapısına dayalı üretimin ise hâlâ baskın olduğunu göstermektedir.

Eğitim düzeyine ilişkin bulgular, bölgedeki insan kaynağının niteliği açısından dikkat çekicidir. Çalışmada üreticilerin çoğunluğunun ilkokul mezunu (%68.8) olduğu, üniversite mezunu üreticinin ise bulunmadığı belirlenmiştir. Benzer şekilde Kaylan (2019), Kayseri bölgesindeki üreticilerin büyük bölümünün ortaokul veya lise mezunu olduğunu, yükseköğrenim düzeyinin ise oldukça sınırlı olduğunu bildirmiştir. Tatar (2007), Kocaman (2014) ve Sevimli (2020) tarafından Ankara ve Aksaray'da yapılan araştırmalarda da üreticilerin büyük çoğunluğunun ilkokul mezunu olduğu saptanmıştır. Bu benzerlik, Türkiye genelinde hayvancılık yapan

kesimin eğitim düzeyinin düşük olması gerçeğini ortaya koymaktadır. Eğitim düzeyinin düşük olması, modern hayvancılık tekniklerinin benimsenmesini, işletme kayıt sisteminin tutulmasını ve yenilikçi teknolojilerin kullanımını sınırlayabilmektedir. Dolayısıyla bölgenin hayvansal üretim potansiyelini artırmaya yönelik eğitim ve yayım çalışmalarının önemini ortaya koymaktadır.

Araştırmada üreticilerin mesleki tecrübelerine bakıldığında, katılımcıların büyük çoğunluğunun 10 yıl ve üzeri tecrübeye sahip olduğu ve özellikle %25,9'unun 26 yıl ve üzeri süredir bu işi yürüttüğü belirlenmiştir. Bu bulgu, hayvancılığın bölgede nesilden nesile aktarılan bir yaşam biçimi olduğunu göstermektedir. Tatar'ın (2019) çalışmasında da üreticilerin %56,3'ünün 26 yıl ve üzeri tecrübeye sahip olduğu belirtilmiştir; dolayısıyla deneyimin özellikle aile işletmelerinde belirleyici bir unsur olduğu anlaşılmaktadır. Ancak bu durum, uzun yıllara dayalı geleneksel deneyimin teknolojik yeniliklere uyumu güçleştirebileceğini de düşündürmektedir.

Genel olarak elde edilen bulgular; Kars ilindeki büyükbaş hayvancılık işletmelerinin, Türkiye'nin birçok bölgesinde olduğu gibi, orta yaş-üstü, düşük eğitim seviyesine sahip fakat yüksek deneyime sahip aile işletmeleri tarafından sürdürüldüğünü göstermektedir. Genç kuşağın hayvancılığa ilgisinin düşük olması, üreticilerin eğitim düzeyinin sınırlı olması ve iş gücü yapısının geleneksel aile modeline dayanması, sektörün modernizasyonu ve sürdürülebilirliği açısından kritik unsurlar olarak değerlendirilebilir. Bu nedenle, hayvancılık sektörünün gelecekte rekabet gücünü koruyabilmesi için gençlerin sektöre kazandırılmasına yönelik teşviklerin artırılması, eğitim-yayım faaliyetlerinin güçlendirilmesi ve aile işletmelerinin teknoloji kullanımını destekleyecek politikaların geliştirilmesi önem taşımaktadır.

Tablo 1. Yetiştiricilerin Genel Özellikleri

Değişkenler	Sayı (adet)	Yüzde (%)
Yaş		
18-25	21	8.6
26-35	66	27.0
36-45	78	32.0
46-55	52	21.3
56-65	26	10.7
66 ve üzeri	1	0.4
İşletmedeki birey sayısı		
1-3	63	25.8
4-6	107	43.9
7 ve üzeri	74	30.3
Eğitim düzeyi		
Okuma-Yazma bilmiyor	1	0.4
Okur-Yazar	4	1.6
İlkokul mezunu	168	68.8
Ortaokul mezunu	10	4.2
Lise mezunu	61	25.0
Üniversite mezunu	0	0
Kaç yıldır bu işi yapıyor		
1-5	12	4.9
6-10	52	21.3
11-15	35	14.3
16-20	47	19.3
21-25	35	14.3
26 ve üzeri	63	25.9

Bu araştırmada Kars ilindeki büyükbaş hayvancılık işletmelerine ait temel yapısal özellikler incelenmiş ve işletmelerin hayvan varlığı, sağmal inek sayısı, ırk tercihleri ve genç hayvan populasyonu bakımından mevcut durumu ortaya konulmuştur. Elde edilen bulgular, bölgedeki hayvancılığın genel karakteristiğinin Türkiye'nin farklı bölgelerinde yapılmış benzer çalışmalarla paralellik gösterdiğini ortaya koymaktadır. Araştırma sonuçları, işletmelerin büyük çoğunluğunun küçük ve orta ölçekli hayvan varlığına sahip olduğunu göstermektedir. Katılımcıların %64.4'ünün 11–30 baş hayvana sahip olması, Kars ilinde büyükbaş hayvancılığın temel olarak orta büyüklükte aile işletmeleri tarafından yürütüldüğünü göstermektedir. Bu bulgu, Erzurum Horasan'da Bastem (2018) tarafından bildirilen; işletmelerin büyük bölümünün 20–40 baş hayvan kapasitesinde olduğu yönündeki sonuçlarla uyum göstermektedir. Her iki araştırma birlikte değerlendirildiğinde, Doğu Anadolu Bölgesi'nde işletme büyüklüklerinin genellikle orta düzeyde yoğunlaştığı görülmektedir.

Sağmal inek sayısına ilişkin bulgular da bu durumu desteklemektedir. İşletmelerin yaklaşık %90'ının 1–10 baş sağmal ineğe sahip olması, süt sığırcılığı faaliyetlerinin Kars'ta büyük ölçüde aile tipi üretim yapısıyla sürdürüldüğünü göstermektedir. Trakya bölgesinde Keskin ve Dellal (2011) tarafından yapılan çalışmada da işletmelerin çoğunluğunun 1–5 baş sağmal ineğe sahip olduğu belirlenmiştir. Bu benzerlik, Türkiye'nin farklı coğrafyalarında süt sığırcılığının genel olarak küçük ölçekli yapıda olduğunu ortaya koymaktadır. Irk tercihleri incelendiğinde işletmelerin %92.2 gibi çok yüksek bir oranla melez ırkları tercih ettiği görülmektedir. Yerli ve kültür ırkı kullanımının oldukça düşük seviyede kalması, bölgedeki üreticilerin verim ve dayanıklılık dengesi bakımından melez ırkları daha avantajlı bulduğunu göstermektedir. Bu eğilim, bölgenin iklim koşullarına uyum gereklilikleri ve bakım maliyetleri dikkate alındığında beklenen bir durumdur. Araştırmanın dikkat çekici bulgularından biri, işletmelerde genç hayvan varlığının büyük oranda sınırlı olmasıdır. İşletmelerin yarısından fazlasında düve (%52.9) ve dana (%51.2) bulunmaması, sürü yenileme stratejisinin çoğu işletmede iç üretimle değil, dışarıdan hayvan teminiyle yürütüldüğünü göstermektedir. Bu durum işletme sürdürülebilirliği açısından risk oluşturmaktadır. Çünkü dışarıdan hayvan satın almak ekonomik maliyeti artırmakta ve sağlık yönetimi açısından ek riskler taşımaktadır. Benzer bir durum, Ödemiş bölgesindeki süt sığırcılığı işletmelerinde de bildirilmiş olup Tatar (2019), işletmelerin büyük bölümünde dana, buzağı ve özellikle besi hayvanı bulundurulmadığını rapor etmiştir. Her iki çalışma birlikte değerlendirildiğinde, Türkiye'nin birçok bölgesinde genç hayvan yetiştiriciliğinin ihmal edildiği ve işletmelerin yenileme materyalini dışarıdan temin etmeye yönelik bir eğilim gösterdiği anlaşılmaktadır. Buzağı varlığının tüm işletmelerde bulunmasına rağmen büyük ölçüde 1–10 baş aralığında yoğunlaşması, işletmelerin buzağı yetiştiriciliğini temel bir faaliyet olarak sürdürse de sürü büyütme stratejilerinin sistematik olmadığına işaret etmektedir. Ayrıca işletmelerin üçte birinde besi hayvanı bulunmaması, Kars ilinde büyükbaş hayvancılığın süt ağırlıklı bir üretim yapısına sahip olduğunu göstermektedir.

Genel olarak bu bulgular, Kars ilindeki büyükbaş hayvancılık işletmelerinin küçük ve orta ölçekli, melez ırka dayalı, dışardan hayvan teminine bağımlı, aile tipi işletme yapısını koruyan bir üretim modeli benimsediğini ortaya koymaktadır. İşletmelerin sürdürülebilirliğinin artırılması için genç hayvan yetiştiriciliğini teşvik eden, iç sürü yenileme oranlarını iyileştiren ve işletme içi damızlık üretimini destekleyen politikaların geliştirilmesi önem taşımaktadır. Ayrıca melez ırkların yaygın kullanımının verimlilik, dayanıklılık ve bölgesel adaptasyon açısından avantaj sağladığı görülmekle birlikte, uzun vadede kültür ırklarının ekonomik olarak daha erişilebilir hâle getirilmesi bölgedeki üretim kapasitesini artırabilecektir.

Tablo 2. İşletmelerde Yetiştirilen Hayvanlara Ait Bilgiler

Değişkenler	Sayı (adet)	Yüzde (%)
İşletmedeki büyükbaş hayvan sayısı?		
1-10 baş	22	9.0
11-20 baş	88	36.1
21-30 baş	69	28.3
31-40 baş	44	18.0
41-50 baş	12	4.9
50 baş ve üzeri	9	3.7
İşletmedeki sağmal hayvan sayısı		
1-5 baş	124	50.8
6-10 baş	95	38.9
11-15 baş	15	6.15
16-20 baş	3	1.25
21-25 baş	4	1.65
26 baş ve üzeri	3	1.25
İşletmelerde tercih edilen ırklar		
Yerli	10	4.1
Melez	225	92.2
Kültür ırkı	9	3.7
İşletmelerdeki düve sayısı		
1-5	75	30.7
6-10	33	13.5
11-15	3	1.2
16-20	2	0.8
21-25	2	0.8
26 ve üzeri	0	0
Bulunmuyor	129	52.9
İşletmelerdeki dana sayısı		
1-5	82	33.6
6-10	33	13.5
11-15	4	1.6
16-20	0	0
21-25	0	0
26 ve üzeri	0	0
Bulunmuyor	125	51.2
İşletmelerdeki buzağı sayısı		
1-5	125	51.2
6-10	97	39.8
11-15	10	4.1
16-20	3	1.2
21-25	2	0.8
26 ve üzeri	7	2.9
Bulunmuyor	0	0
İşletmelerdeki besi hayvanı sayısı		
1-5	36	14.8
6-10	68	27.9
11-15	40	16.4
16-20	13	5.3
21-25	1	0.4
26 ve üzeri	1	0.4
Bulunmuyor	85	34.8

Sonuç olarak, bu çalışma Kars ilinde büyükbaş hayvancılığın mevcut yapısının Türkiye'deki genel eğilimlerle uyumlu olduğunu, geleneksel aile işletmeciliği şeklinde devam ettiğini, ancak özellikle genç hayvan yetiştiriciliği ve sürü yenileme konularında iyileştirmeye ihtiyaç duyulduğunu göstermektedir. Bu kapsamda destekleme politikalarının yeniden ele alınması, üreticilerin teknik bilgi ve uygulama kapasitesinin artırılması ve işletme yönetim planlarının daha uzun vadeli bir bakış açısıyla şekillendirilmesi sektörün gelişimi açısından kritik önem taşımaktadır.

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THE ROLE OF UPSTREAM COMMUNITY KNOWLEDGE IN SUPPORTING THE SUSTAINABILITY OF WATER ENVIRONMENTAL SERVICES CONSERVATION IN THE WAY SEKAMPUNG SUB-WATERSHED

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ABSTRACT

Community understanding and awareness serve as a crucial foundation in maintaining the sustainability of natural resources, particularly in the upstream areas of watersheds. Communities with a higher level of knowledge about conservation tend to manage their environment in a more sustainable manner. Water ecosystem services include ecological benefits that support human life, such as clean water provision, flood control, and water quality maintenance. Thus, the relationship between humans and water resources in upstream areas is often reciprocal. The Sub-Watershed Way Sekampung in Lampung Province is one of the key areas that plays a major role in supplying water for agricultural, domestic, and industrial needs in the downstream region. This study aims to identify the role of upstream communities in the Way Sekampung Sub-Watershed in supporting the sustainability of water ecosystem service conservation. The research was conducted using a qualitative method with a descriptive approach, namely a study that seeks to describe phenomena based on literature analysis through the concept of a systematic review, which aims to collect evidence to answer predetermined research questions. Upstream communities show an 83% level of willingness to participate in conservation activities, particularly when economic incentives are provided through the Payment for Environmental Services (PES) scheme. Previous studies also indicate that approximately 78.4% of upstream communities in the Kambaniru watershed understand the relationship between forest cover and water availability, and 72% of them are directly involved in conservation activities such as tree planting and water resource management. These findings demonstrate that community participation and water ecosystem service conservation are positively correlated, highlighting the vital role of local communities in ensuring environmental sustainability.

Keywords: Conservation, communities role, water ecosystem services

INTRODUCTION

Community understanding and awareness are fundamental in maintaining the sustainability of natural resources, particularly in upstream watershed areas (Gupta *et al*., 2022). Communities with a high level of knowledge regarding conservation are generally more capable of managing their environment in a sustainable manner. They understand that every action—such as cropping patterns, land-use practices, or water management—has direct consequences for ecosystem balance. Therefore, environmental literacy becomes a key aspect in ensuring that conservation efforts are not temporary but remain sustainable over the long term.

Conservation activities play an essential role in maintaining ecosystem functions, including the preservation of water environmental services. Water environmental services encompass ecological benefits that support human life, such as providing clean water, regulating floods, and maintaining water quality. When conservation activities are not optimally implemented, these functions may decline, leading to reduced land productivity, increased hydrological disaster risks, and decreased water availability for downstream communities. Hence, community involvement in maintaining the sustainability of water environmental services is crucial, especially for upstream communities who directly influence water quality and quantity (Environmental Management, 2022).

The relationship between humans and water resources in upstream areas is often reciprocal. On one hand, upstream communities depend on water resources for domestic and agricultural needs (Pamungkas *et al*., 2023). On the other hand, they serve as key actors in maintaining water availability for downstream regions. Conservation practices carried out by upstream communities—such as tree planting, agroforestry, and efficient water use—have significant impacts on sustaining water environmental services at the sub-watershed level. Thus, strengthening upstream community knowledge on sustainable water resource management is a crucial factor in maintaining watershed ecosystem stability.

The Way Sekampung Sub-Watershed in Lampung Province is an important area that significantly contributes to water supply for agriculture, domestic use, and industry in downstream regions. The biophysical conditions of the upstream area show vulnerability to environmental degradation due to land-cover change and intensive human activities. Land clearing, forest conversion, and limited adoption of soil and water conservation techniques are major threats to water sustainability. In this context, the level of knowledge and awareness among upstream communities regarding the importance of conservation becomes a determining factor for effective watershed management (Andriyani *et al*., 2021).

Several previous studies have shown that the success of conservation programs in upstream areas heavily depends on community understanding of environmental management concepts (Yumantoko *et al*., 2024). Communities who understand the ecological functions of forests and water resources tend to participate more actively in conservation activities than those lacking environmental awareness. This reinforces that conservation efforts require not only policy and technology support, but also behavioral change rooted in local knowledge. Therefore, understanding the knowledge level of upstream communities is an essential first step in designing effective and participatory conservation strategies in the Way Sekampung Sub-Watershed.

Based on these conditions, this study focuses on analyzing the role of upstream community knowledge in supporting the sustainability of water environmental services conservation in the Way Sekampung Sub-Watershed. The study is expected to provide deeper insights into the relationship between community knowledge and water resource conservation efforts. Its results

may serve as a basis for policymakers and environmental managers to formulate adaptive, equitable, and community-based watershed management strategies.

PURPOSE

This study aims to identify the role of upstream communities in the Way Sekampung Sub-Watershed in supporting the sustainability of water environmental services conservation.

METHOD

This research was conducted using qualitative methods through a descriptive approach, aiming to describe a phenomenon based on a literature review using the systematic review concept, which seeks to gather evidence to answer predetermined research questions (Pollock et al., 2018). This approach involves identifying all primary studies relevant to the topics of conservation, environmental knowledge, and water environmental services in upstream watershed areas, followed by critical appraisal of their methodological quality and synthesis of findings to produce a scientifically accountable and comprehensive overview.

This research also utilizes secondary data from previous studies that measure community knowledge, conservation participation, and the economic value of water environmental services, both in the Way Sekampung Sub-Watershed and in comparable watersheds. These secondary data are used to build comparative tables, supporting graphs, and strengthen discussions regarding the relationship between community knowledge and water environmental services sustainability.

The tools and materials for this study include a list of questions or questionnaires, field note books (tally sheets), stationery, calculating tools, computers, and cameras. Although this research does not collect primary data directly, these instruments are prepared as part of the research framework that may be utilized in future field studies. Data analysis was conducted using descriptive techniques by summarizing findings, connecting patterns across variables, and developing interpretations to explain the role of upstream community knowledge in supporting conservation and sustainability of water environmental services in the Way Sekampung Sub-Watershed.

RESULTS AND DISCUSSION

1. Knowledge Condition of Upstream Communities in the Way Sekampung Sub-Watershed

The results of the literature review show that communities in the upstream areas of the watershed generally have a fairly good level of understanding regarding the relationship between land cover, vegetation presence, and water availability. Several relevant studies, such as Vatir et al. (2022), found that **78.4%** of upstream communities understand that forest degradation reduces water discharge and increases the risk of drought. This finding is supported by other studies on tropical watersheds, which indicate that environmental literacy among upstream communities is directly associated with awareness of water resource conservation (Suharno et al., 2021).

In the context of the Way Sekampung Sub-Watershed, secondary data reveal similar trends, where communities understand the importance of buffer vegetation, riparian protection, and environmentally friendly land management. This level of understanding serves as an initial asset in encouraging their participation in water conservation programs. The measurement of environmental knowledge among upstream communities is presented in **Table 1**.

Table 1. Instrument for Measuring Environmental Knowledge

Variable	Measurement Indicators	Likert Scale (1-5)
Factual Knowledge	Understanding forest functions, water quality, hydrological cycle	1: Very Knowledgeable 2: Knowledgeable 3: Neutral 4: Unkowledgeable 5: Very Unknowledgeable
Conceptual Knowledge	Understanding the relationship between conservation and water environmental services	1: Very Knowledgeable 2: Knowledgeable 3: Neutral 4: Unkowledgeable 5: Very Unknowledgeable
Procedural Knowledge	Understanding how to perform conservation activities such as tree planting and spring rehabilitation	1: Very Knowledgeable 2: Knowledgeable 3: Neutral 4: Unkowledgeable 5: Very Unknowledgeable

2. Conservation Practices Conducted by Upstream Communities

The relatively good level of knowledge is reflected in the involvement of upstream communities in various forms of conservation activities. Several studies in comparable watersheds show that more than **70%** of local communities participate in forest rehabilitation, tree planting, spring protection, and land clearing restrictions (Rahmadani et al., 2023). In the Way Sekampung Sub-Watershed, these practices are primarily driven by the community's need for clean water for domestic and agricultural use. Communities have also begun implementing simple agroforestry techniques and reducing land-burning practices. These findings indicate that communities not only understand conservation concepts but have also implemented concrete actions that support the restoration and sustainability of water environmental services. The measurement conservation participation among upstream communities is presented in **Table 2**

Table 2. Instrument for Measuring Conservation Participation

Variable	Measurement Indicators	Likert Scale (1-5)
Physical Participation	Direct involvement in conservation activities	1: Very Often 2: Often 3: Between Times 4: Infrequent 5: Never
Management Participation	Attendance in meetings, forest farmer groups, or monitoring activities	1: Very Often 2: Often 3: Between Times 4: Infrequent 5: Never
Decision-Making Participation	Involvement in planning conservation activities	1: Very Often 2: Often 3: Between Times 4: Infrequent 5: Never

3. Relationship Between Environmental Knowledge and the Sustainability of Water Environmental Services

The environmental knowledge level of upstream communities is directly proportional to the quality of water source management and the sustainability of environmental services produced. Muslihat et al. (2022) found that ecological literacy among upstream communities can increase conservation effectiveness by **23–40%**, especially in areas dependent on surface water. In the Way Sekampung Sub-Watershed, communities that understand the impacts of land-use change are more active in maintaining vegetation cover and reducing riparian degradation. This involvement has a direct effect on the sustainability of downstream water flow, which relies on stable discharge from the upstream region. Therefore, knowledge acts as a fundamental factor determining the quality and continuity of water environmental services.

4. Comparison of Upstream Community Participation in Way Sekampung and Other Watersheds in Indonesia

Compared to other watersheds in Indonesia, the level of upstream community participation in Way Sekampung is relatively high and stable. For example, in the Kambaniru Watershed (NTT), only 72% of households participate in spring protection (Vatir et al., 2022), while in the Ciliwung Watershed participation levels are around **55–60%** (Pradana et al., 2021).

Tabel 3. Comparison of Upstream Community Participation

Watershed Region	Knowledge Level	Conservation Participation	Explanation
Way Sekampung (Lampung)	83% (High)	82% (Very Active)	High understanding of water conservation; active in spring protection & agroforestry
Kambaniru (East Nusa Tenggara)	78.4% (Moderate)	72% (Active)	Strong understanding of forest–water relationship
Ciliwung (West Java)	60% (Low)	55% (Less Active)	Low participation due to urban pressure & weak local institutions

Watershed possess the highest environmental knowledge level compared to the two comparative watersheds—**83%**, higher than Kambaniru (78.4%) and Ciliwung (60%). This reflects the influence of environmental education, firsthand experience with declining water quality, and interaction with government or NGO programs. Conservation participation in Way Sekampung is also the highest (**82%**) compared to Kambaniru (72%) and Ciliwung (55%).

These data demonstrate that environmental knowledge is directly correlated with involvement in tree planting, spring protection, land management, and community-based conservation.Upstream communities in Way Sekampung show stronger engagement due to their direct dependency on water resources and the visible impacts of environmental degradation experienced over recent decades.This positions Way Sekampung as a strong candidate for community-based conservation schemes such as **Payment for Environmental Services (PES)**.

5. Factors Encouraging Conservation Participation

Upstream community participation in conservation activities is influenced not only by their level of environmental knowledge but also by social, economic, and ecological factors shaping their motivation to engage. In the Way Sekampung Sub-Watershed, the relatively high participation level is driven by the community's direct reliance on sustainable water resources

for domestic use, agriculture, and local economic activities. Additionally, past experiences with reduced water quality and quantity have strengthened the collective awareness that conservation is a shared responsibility that must be carried out sustainably.

Institutional and external support also plays a crucial role. The presence of forest farmer groups (KTH), customary institutions, and community empowerment programs enhances coordination and facilitates conservation activities. Guidance from village governments, forestry agencies, and universities increases community capacity in managing water resources effectively. Financial incentives through schemes such as PES further encourage community involvement, as people feel appreciated for protecting the environment. The following factors support conservation participation are below this

- **Environmental Knowledge**

Understanding forest functions, hydrological processes, and the relationship between land cover and water discharge increases community awareness of the importance of conservation.

- **Economic Dependence on Water Resources**

Communities reliant on water for farming, small enterprises, and household needs are more active in sustaining water resources.

- **Strong Local Institutions**

KTH groups, river-care communities, and customary bodies strengthen coordination, rule-making, and shared responsibilities.

- **Experience with Environmental**

Those who have experienced drought, water shortages, or degraded springs are more motivated to prevent future occurrences.

- **Government and Stakeholder Support**

Training, extension programs, and mentoring enhance community skills in conservation practice.

- **Financial Incentives and PES**

Economic rewards motivate higher participation, especially in communities with economic vulnerabilities.

- **Social Capital and Community Solidarity**

Strong social ties, shared norms, and mutual cooperation increase willingness to join conservation efforts.

- Access to Information and Education

KEnvironmental campaigns, community-based monitoring, and educational programs broaden awareness and support collective conservation initiatives.

6. Challenges and Opportunities for Strengthening Conservation in the Upstream Region

Although knowledge and participation levels are relatively high, several challenges remain, particularly in funding availability, institutional capacity, and limited access to advanced environmental education. Siregar et al. (2021) highlight that the success of upstream conservation is also influenced by household economic stability. In Way Sekampung, many

communities still rely on dryland agriculture, making them economically vulnerable and potentially decreasing long-term conservation participation.

However, opportunities remain strong through PES programs, government–community partnerships, strengthened environmental education, and the integration of community-based water monitoring technologies.

CONCLUSION

This study demonstrates that upstream community knowledge plays a crucial role in supporting the sustainability of water environmental services conservation in the Way Sekampung Watershed. High levels of environmental literacy encourage active community participation in conservation practices such as spring protection, tree planting, and agroforestry-based land management. These actions contribute directly to stabilizing water discharge and improving water quality flowing toward downstream areas.

Secondary data show that upstream communities in the Way Sekampung Watershed possess higher levels of environmental knowledge and participation compared to several other watersheds in Indonesia. This indicates that ecological experience, economic dependence on water resources, and institutional support significantly influence conservation behavior. Strengthening environmental education, empowering local communities, and expanding incentive mechanisms such as PES represent strategic opportunities for improving community-based watershed management.

Overall, this study emphasizes that water resource conservation is influenced not only by biophysical conditions but also by the quality of community knowledge, behavior, and participation. Therefore, integrating ecological and social approaches is essential for achieving sustainable, equitable, and adaptive watershed management in the Way Sekampung Watershed.

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COMPARATIVE ANALYSIS OF METEOROLOGICAL DROUGHT BY DROUGHT INDICES AND TREND TECHNIQUES: THE CASE OF IZMIR

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ABSTRACT

As an extreme nature event and recurrent natural disaster, drought is a formation that impacts live life and ecosystems negatively and harms to water that is ultimately required for vital activities and its related sectors such agriculture and energy. In this study, obtaining mean monthly temperature and monthly total precipitation data of 17220-İzmir Bölge Station and using Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), Reconnaissance Drought Index (RDI), Z-Score Index (ZSI) and Rainfall Anomaly Index (RAI), drought analysis of İzmir province are analyzed for the time scales of 1, 3, 6, 9, 12-month. Possible trends in the time series of indices are examined by Mann-Kendall (MK), Spearman Rho (SR) and Sen Slope (SS) tests. The relations between indices are investigated by Kendall' τ correlation test. The results have shown that normal drought category has been dominant in all time scales of all indices. According to results of MK and SR tests considering α=0.01, there has been a significant increasing trend SPI-3, 6, 9, 12-months, ZSI-12-month and RAI-3, 6, 9, 12-months series while a significant decreasing trend has been observed in all time series of SPEI. SS test results have demonstrated that all time series of SPI, ZSI and RAI indices have a positive trend slope while all SPEI series have negative trend slope. Correlation results have shown that indices may have similarities either in same or different time scales since a strong correlation has been obtained many times. The results of this study are expected to be beneficial for the drought mitigation and water resources management plans of the region.

Keywords: Drought, Turkiye, Izmir, SPI, SPEI, RDI, ZSI, RAI, Trend, Correlation

1. INTRODUCTION

Drought have been defined as repeated natural disaster that has impacts on water supply, energy and health (Rahman et al., 2025). It has been stated by (Ali et al., 2025; FAO, 2021) there has been an estimated USD 29 billion in economic damages was attributed to drought events during the period 2005–2015. In many studies such as (Dodangeh et al., 2025; Rahman et al., 2025; Wilhite & Glantz, 1985; Yuce et al., 2023) drought has been classified with 4 groups which are meteorological, agricultural, hydrological and socio-economic. Among these categories, meteorological drought has been defined with deficiency of precipitation (Oyarzabal et al., 2025).

Monitoring the drought events has a critical role in struggling with natural disasters, management of water resources and preparing action plans. For drought monitoring many drought indices have been developed such as Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), Reconnaissance Drought Index (RDI), Z-Score Index (ZSI) and Rainfall Anomaly Index (RAI). At least one of these indices have been used in many drought monitoring studies such as (Adnan et al., 2018; Akşan & Bacanlı, 2021; Dikici & Aksel, 2021; Dogan et al., 2012; Jain et al., 2015; Katipoğlu et al., 2020; Mashari Eshghabad et al., 2014; Öz et al., 2024; Wable et al., 2019; Yuce & Esit, 2021; Zarei et al., 2021) for many parts of the world and Turkiye.

In drought monitoring, trend detection techniques provide understanding temporal variability of time series for further predictions. For examination of possible trends Mann Kendall Test (Kendall, 1975; Mann, 1945), Spearman's Rho Test (Spearman, 1961), Innovative Trend Analysis (Şen, 2012) have been widely used and Sen's Slope Test (Sen, 1968) have been utilized for trend slope determination. In many studies such as (Deger et al., 2025; Kartal & Emiroglu, 2024; Meskelu et al., 2024; Oubadi et al., 2024; Yaşa & Partal, 2024) have been effectively used. In another examination perspective, the correlation between time series of indices have been investigated by some correlation coefficients such as Pearson, Spearman and Kendall in the studies such as (Mliyeh et al., 2025; Pandya & Gontia, 2024).

In this study, a comprehensive meteorological drought monitoring study has been done for Izmir Region of Turkiye using SPI, SPEI, RDI, ZSI and RAI indices for the time scales of 1, 3, 6, 9, 12-month. Possible trends at time series of drought indices have been examined by Mann-Kendall (MK), Spearman Rho (SR) and trend slopes have investigated by Sen's Slope Test (SS). The relations between indices are investigated by Kendall (τ) correlation test. For making the analysis, mean monthly temperature and monthly total precipitation data of 17220-İzmir Bölge Station have been acquired from General Directorate of Meteorology of Turkiye. The findings of this study are expected to be useful for local authorities in drought action and water resources management plans.

2. METHODOLOGY

2.1. Drought Indices

2.1.1. Standardized Precipitation Index (SPI)

SPI that was developed by (McKee et al., 1993) has one of the most commonly used indices for drought monitoring (Akbas et al., 2025). It has been stated by Sobral et al. (2019) that SPI is recommended by World Meteorological Organization. Before application of SPI, gamma distribution function is applied to monthly rainfall data with the following manner (Esit & Yuce, 2023; Robleh et al., 2024). The probability distribution function of gamma distribution function is computed by Equation 1.

$$g(x) = \frac{1}{\beta^a \Gamma(a)} x^{a-1} e^{-\frac{x}{\beta}} \quad (1)$$

Where *Γ(a)* describes the gamma function and it can be determined by Edwards (1997).

$$\Gamma(a) = \int_0^\infty y^{a-1} e^{-y}\, dy \quad (2)$$

According to maximum likelihood method estimation, shape (α), scale (β) parameters are determined by Thom (1966) with following equation:

$$a = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \quad (3)$$

$$\beta = \frac{\bar{x}}{a} \quad (4)$$

where A is computed by (Thom, 1966) as

$$A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n} \quad (5)$$

Where *n* represents the number of rainfall records and $\bar{x}$ is the mean of x.

Then cumulative distribution function is calculated by Equation 6 (Thom, 1966).

$$H(x) = q + (1 - q)G(x) \quad (6)$$

Where q is the probability of zero and *G(x)* describes the cumulative distribution for the selected month and time scale. If m is denoted as the number of zeros, then *q* is determined by *q=m/n* (Thom, 1966). After all, *H(x)* is transformed to the standard normal variable Z whose mean and variance are 0 and 1 respectively describing the SPI with Equation 7 (Robleh et al., 2024).

$$SPI = \frac{X_{ij} - \bar{X}_{im}}{\sigma} \quad (7)$$

2.1.2. Standardized Precipitation Evapotranspiration Index (SPEI)

SPEI was developed by (Vicente-Serrano et al., 2010). It provides more comprehensive evaluation of drought conditions as it joins the precipitation and temperature (Öllükçü & Katipoğlu, 2025) According to determination procedure of this index, firstly potential evopotranspiration that is PET is calculated using Thornthwaite Method (Thornthwaite, 1948) by Equation 8.

$$PET = 16d\left(\frac{10T}{I}\right)^a \quad (8)$$

where; T shows the monthly mean temperature in units of °C, *I* represents a heat index, α is a coefficient dependent on *I* and d which can be acquired from latitude-specific tables represents a correction factor for monthly diurnal duration variation. The difference between the precipitation and PET for the *i* month is calculated from Equation 9 (Vicente-Serrano et al., 2010).

$$D_i = P_i - PET_i \quad (9)$$

Then D values are summed up at different time scales (Esit et al., 2025).

$$D_n^k = \sum_{i-0}^{k-1} P_{n-1} - (PET)_{n-1} \quad (10)$$

where k describes aggregation period in months, n shows the calculation month. Then, the log-logistic probability density function is described as in Equation 11:

$$f(x) = \frac{\beta}{\alpha}\left(\frac{x-y}{a}\right)^{\beta-1}\left(1+\left(\frac{x-y}{a}\right)^{\beta}\right)^{-2} \quad (11)$$

As α, β, and γ are scale, shape, and origin parameters (γ > D < ∞) respectively, the probability distribution function for the D series becomes as in the Equation 12:

$$f(x) = \left[1+\left(\frac{a}{x-y}\right)^{\beta}\right]^{-1} \quad (12)$$

Then SPEI is derived by standardizing F(x) values benefiting the approximation of Abramowitz and Stegun (1968).

$$SPEI = W - \frac{C_0+C_1W+C_2W^2}{1+d_1W+d_2W^2+d_3W^3} \quad (13)$$

$$W = \sqrt{-2In(P)}\ for\ P \leq 0.5 \quad (14)$$

where $C_0 = 2.515517$, $C_1 = 0.802853$, $d_1 = 1.432788$, $d_2 = 0.189269$, $d_3 = 0.001308$.

2.1.3. Reconnaissance Drought Index (RDI)

RDI that has been developed by (Tsakiris & Vangelis, 2005) has the following determination procedure: Firstly, the initial value of index which is a_k is determined by Equation 15.

$$a_k = \frac{\sum_{j=1}^{j=k} P_j}{\sum_{j=1}^{j=k} PET_j} \quad (15)$$

Where P_J and PET_J shows the precipitation and potential evapotranspiration of the j-th month. Here RDI can be determined either as normalized RDI_n or standardized RDI_{st} via Equation 16 and Equation 17 respectively. The computation procedure of RDI_{st} is very similar to determination of SPI (Tsakiris & Vangelis, 2005; Yuce & Esit, 2021).

$$RDI_n(k) = \frac{a_k}{\bar{a}_k} - 1 \quad (16)$$

$$RDI_{st}(k) = \frac{y_k-\bar{y}_k}{\bar{\sigma}_k} - 1 \quad (17)$$

Where y_k is ln a_k , $\bar{y}_k$ represents arithmetic mean and $\bar{\sigma}_k$ denetotes the standard deviation.

2.1.4. Rainfall Anomaly Index (RAI)

Developing by (Van Rooy, 1965) rainfall anomaly index is a drought index that is ranking based (M. Aydin, 2025). The RAI can be assessed via following equations of 18 and 19 (Katipoğlu et al., 2020).

$$RAI = +3\ \frac{P-\bar{P}}{\bar{M}-\bar{P}} \quad (18)$$

$$RAI = -3\ \frac{P-\bar{P}}{\bar{X}-\bar{P}} \quad (19)$$

Where $\bar{P}$ shows average of precipitation series, $\bar{M}$ describes the average of the highest 10 values and $\bar{X}$ denotes the average of the smallest ten values. When P > $\bar{P}$ the anomaly becomes positive, if P < $\bar{P}$ the anomaly is negative.

2.1.5. Z-Score Index (ZSI)

ZSI is an another index that is used in drought monitoring studies such as (Katipoğlu et al., 2020; Yuce & Esit, 2021; Zeybekoglu, 2025) and not require data fitting. ZSI can be determined from Equation 20.

$$ZSI = \frac{X_i - \bar{x}}{\sigma} \tag{20}$$

2.2. Drought Categories

For a detailed drought and as well as the wet conditions assessment, after determination of values of indices in different time scales, each indices value is associated with a dry or wet category given in Table 2.1

Table 2.1. Dry and wet classifications (Yuce & Esit, 2021)

Drought Class	SPI, SPEI, RDI, ZSI	RAI
Extremely Wet	≥ 2	≥ 3
Very Wet	1.5-1.99	
Moderately Wet	1.00-1.49	
Normal	0.99 to -0.99	0.5 to -0.99
Moderately Dry	-1.00 to -1.49	-1.00 to -1.99
Very Dry	-1.5 to -1.99	-2.00 to -2.99
Extremely Dry	≤ -2	≤ -3

2.2. Trend Techniques

2.2.1. Mann-Kendall Test (MK)

MK that has been developed by (Kendall, 1975; Mann, 1945) is a well-known test is continuously used for trend detection in drought monitoring studies (Chitsaz & Hosseini-Moghari, 2017; Deger et al., 2025; Zarei, 2019). The Z statistics of the test determined via following procedure.

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k) \tag{21}$$

$$sgn(x_j - x_k) = \begin{cases} 1 & (x_j - x_k) > 0 \\ 0 & (x_j - x_k) = 0 \\ -1 & (x_j - x_k) < 0 \end{cases} \tag{22}$$

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_i^m t_k(t_k-1)(2t_k+5)}{18} \tag{23}$$

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & S < 0 \end{cases} \tag{24}$$

Where n denotes the number of data x_i and x_j describe data points in the years of j and k (j>k) respectively and Var(S) is used in case of having ties. When Z>0 then there is a increasing trend and when Z<0 there is a presence of decreasing trend. For significance cases, trends are assessed based on a significance level. In the study α=0.01 ($Z = \pm 2.576$) is considered.

2.2.2. Spearman's Rho Test (SR)

SR which is a rank-based non parametric test is another most widely used test for trend detection as it has been recently used in many studies such as (Güner Bacanli, 2017; Simsek et al., 2025). In the test correlation coefficient r_s and the test statistic Z can be calculated by Equation 25 and Equation 26 respectively (H. Aydin et al., 2025). The interpretation of Z values is same with MK test. In the study α=0.01 ($Z = \pm 2.576$) are taken into account for trend evaluation.

$$r_s = 1 - \frac{[6\ \sum_{i=1}^{n}(Rx_i - i)^2)]}{n(n^2-1)} \quad (25)$$

$$z = r_s\sqrt{n-1} \quad (26)$$

2.2.3. Sen's Slope Test (SS)

For determination of trend slopes, SS test that has been developed by (Sen, 1968) is used. During the test trend slope are determined via Equation 27 and Equation 28.

$$S = \frac{Q_2 - Q_1}{T_2 - T_1} \quad (27)$$

$$S = \begin{cases} S_{\frac{n+1}{2}} & n = even \\ S_{\frac{n}{2}} & n = odd \end{cases} \quad (28)$$

2.3. Correlation Analysis

2.3.1. Kendall's τ Correlation Coefficient

In the study, correlation between indices have been examined by a well-known coefficient of Kendall's **τ** that has been used in many hydrology studies such as (Chitsaz & Hosseini-Moghari, 2017; Yuce & Esit, 2021). The details of this coefficient can be seen in (Aon & Biswas, 2024; Shao et al., 2025).

3. STUDY AREA AND DATA

İzmir which is found in Aegean region of Turkiye is the third largest city of the country (Çilingir et al., 2026; Erdoğan, 2025). The city where mediterranean climate in which summers are hot and dry and winters are mild and rainy is seen has a surface area of 12.012 km^2 (Öztürk et al., 2025). In the study, mean monthly temperature (°C) and monthly total precipitation (mm) data of 17220-İzmir Bölge meteorological station during data record of 1950-2024 have been taken from General Directorate of Meteorology of Turkiye for performing analysis. The information of this data has been given in Table 3.1 while the location of Izmir city and 17220 İzmir Bölge meteorological station have been presented in Figure 3.1. According to Table 3.1, mean monthly temperature has been ranged with 5.30-30.90 (°C) while monthly total

precipitation series have been ranged as 0-411.6 mm during data record. During 1950-2024, mean temperature and mean monthly total precipitation have been 18.05 (℃) and 58.71 mm.

Table 3.1 Information of used station and meteorological variables

Station Name	Latitude (N)	Longitude (E)	Height (m)	Meteorological Variable	Data Range	Mean	Standard Deviation	Minimum	Maximum
17220 İzmir Bölge	38.3949	27.0819	29	Mean Monthly Temperature (℃)	1950-2024	18.05	6.95	5.30	30.90
				Monthly Total Precipitation (mm)		58.71	67.57	0.00	411.60

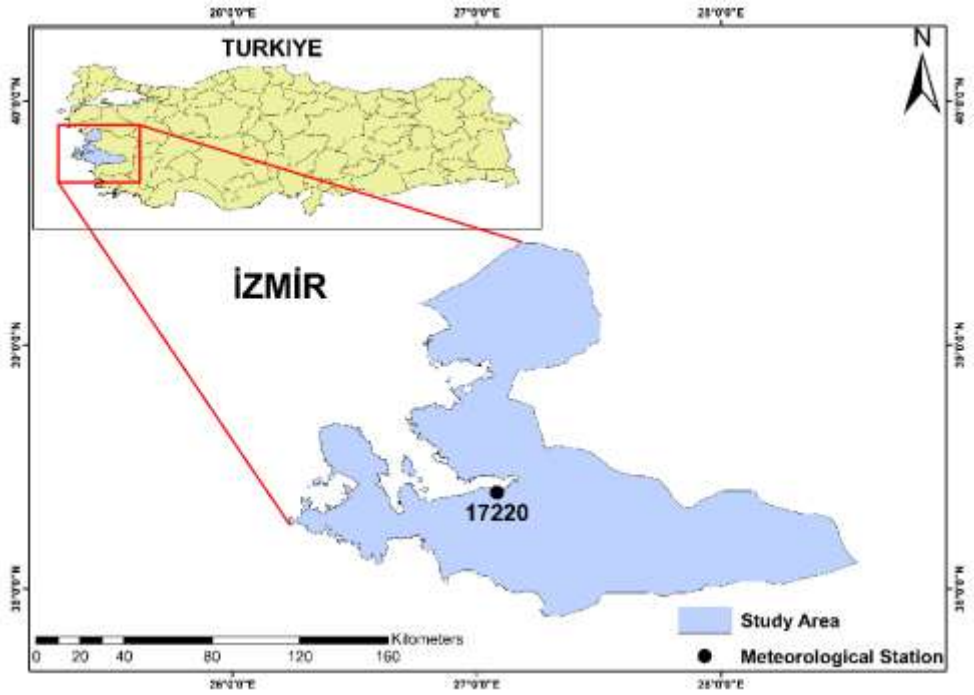

Figure 3.1. Study area and location of meteorology station

4. RESULTS AND DISCUSSIONS

4.1. Examination of Time Series of Indices

In the study using SPI, SPEI, RDI, ZSI and RAI algorithms, the dry (drought) and wet events have been determined. To make the evaluations easier, determined indices have been illustrated with Figure 4.1. These graphs aid to researchers in the first evaluation of outcomes by indices as visual. As it can be seen many drought (dry) events have happened even near today. With the increment of time scale, drought events have become longer in all indices. As it can be seen, many times indices have captured the droughts at the same time.

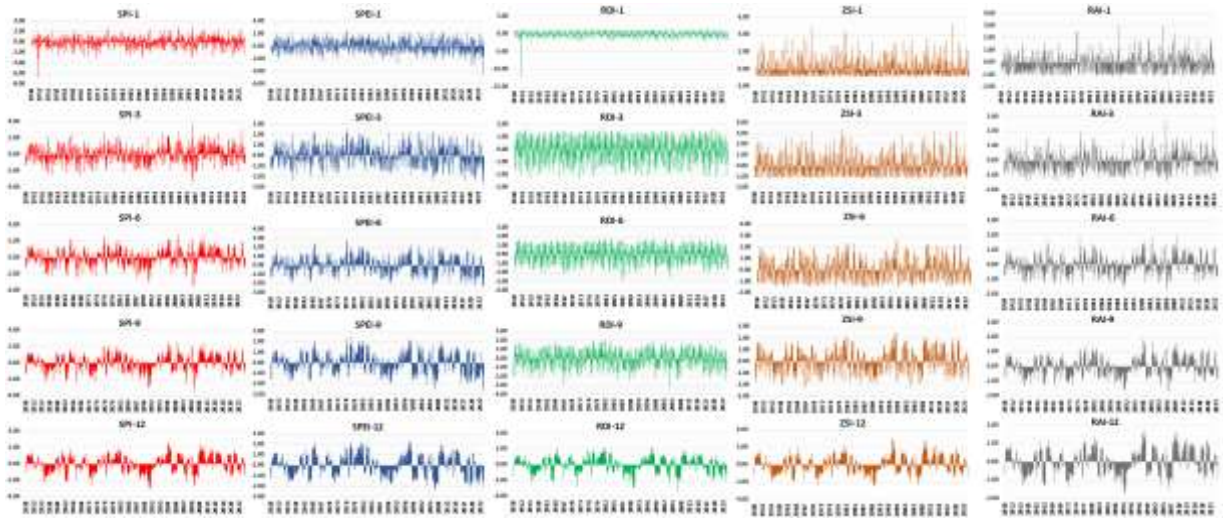

Figure 4.1. Time Series of Indices in the time scales of 1, 3, 6, 9, 12-month

4.2. Dry and Wet Categories Distribution

For a comprehensive monitoring of drought and as well as the wet events, each indices value has been associated with a dry/wet category based on its value. For easiness, all wet categories have been combined under the name of "Wet" category. Then the distribution of indices in dry/wet categories have been investigated considering percentage of occurrence (%). By doing this, all results have been given with Figure 4.2. As it can be seen from the figure that normal dry category and wet category have the superiority among all categories. In SPI series, normal category has the range of (27.7%-32.1%) and wet category has the (48.4%-58.2%). In SPEI series normal category and wet category have been ranged as (30.1%-33.1%) and (49.4%-50.3%) respectively. In RDI, the normal category has been recorded with the range of (26.1%-34.1%) while wet has been recorded with the range of (49.8%-54%). In ZSI, the range of normal category has been (32.7%-63.9%) and while wet has been ranged as (36.1%-47.3%). When it comes to RAI, the normal category has been recorded with the range of (69.9%-78%) and wet has become as (14.7%-25.4%). Among these indices the normal category has reached its maximum in RAI-1 while its minimum in RDI-3 series. The wet conditions have occurred as maximum in SPI-1 and as minimum in RAI-1. Other dry categories moderately dry, very dry and extreme dry have been detected with the ranges of (0-19.44%), (0-7.67%) (0-3.78%).

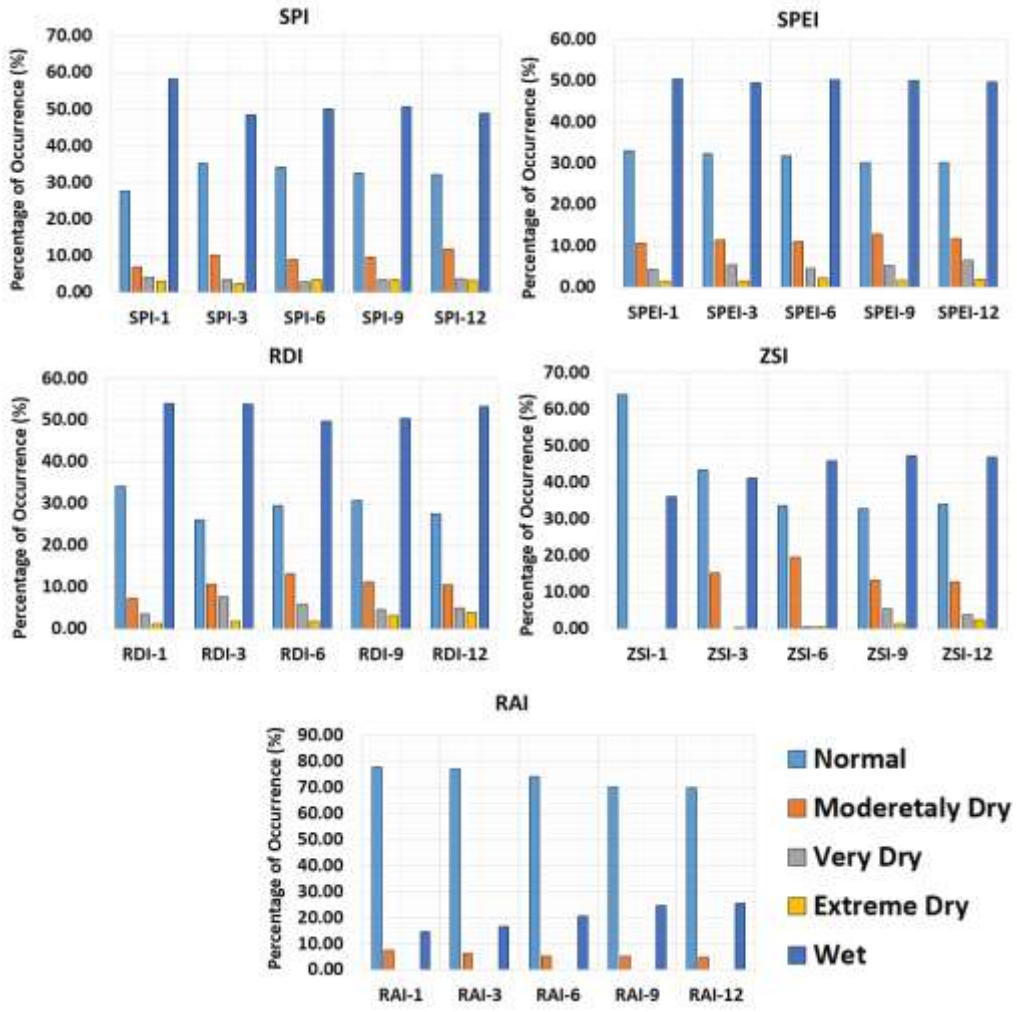

Figure 4.2. Dry and wet category distribution of indices across 1, 3, 6, 9, 12-month time scales based on percentage of occurrence (%)

4.3. Trend Detection Analysis

In order to detect possible trends in time series of indices, MK and SR tests have been applied. Considering significance level of α=0.01 level ($Z = \pm 2.576$), significance conditions of series have been examined. The results of the trend tests have been given with Table 4.1. For easiness trend types (either increasing or decreasing) have been illustrated by different colors and significant trends have been shown by italic and bond font. In SPI series, results of both tests have shown that the series have had increasing trends and in 3, 6, 9, 12-month series these trends have been significant since Z values of them have been bigger than 2.576. In SPEI series the trends of the series have been significantly decreasing trends. In RDI series, the series have been more variable in terms of trend types but nevertheless these trends have been non-significant. In ZSI series, except at ZSI-12, all trend results have occurred from non-significant increasing trends while ZSI-12 has been detected with significant increasing trends. Similar to SPI series, in RAI series, significantly increasing trends have been detected in 3, 6, 9, 12-month. As it can be seen from the table that, in all the series MK and SR have given similar results in terms of trend types and significance conditions.

Table 4.1. Trend detection results of MK and SR tests

(The bold and italic font shows significance level for α=0.01 significance level)

	SPI-1	SPI-3	SPI-6	SPI-9	SPI-12
MK	1.75645	***2.76303***	***3.10421***	***2.96308***	***3.13090***
SR	1.72094	***2.79459***	***3.12709***	***3.09098***	***3.37340***
	SPEI-1	**SPEI-3**	**SPEI-6**	**SPEI-9**	**SPEI-12**
MK	***-3.31149***	***-3.14187***	***-2.64858***	***-2.70795***	***-3.20055***
SR	***-3.31247***	***-3.17623***	***-2.73936***	***-2.71934***	***-3.19271***
	RDI-1	**RDI-3**	**RDI-6**	**RDI-9**	**RDI-12**
MK	0.07351	0.30239	0.27367	-0.36108	-1.58456
SR	0.09779	0.34046	0.26455	-0.39076	-1.52317
	ZSI-1	**ZSI-3**	**ZSI-6**	**ZSI-9**	**ZSI-12**
MK	0.92906	1.37978	1.73836	2.34698	***3.12287***
SR	0.93322	1.44379	1.75255	2.33565	***3.34554***
	RAI-1	**RAI-3**	**RAI-6**	**RAI-9**	**RAI-12**
MK	1.67044	***2.78658***	***3.12686***	***2.98278***	***3.12980***
SR	1.62261	***2.82496***	***3.14384***	***3.10231***	***3.37911***
	Increasing Trend			**Decreasing Trend**	

In order to examine the trend slope of the series, SS tests have been applied and the results have been given with Table 4.2. As it can be seen from the table that in all series SPI, ZSI, RAI trend slopes have been positive indicating an increasing trend. In SPEI series all series have been detected with negative slopes indicating a decreasing trend. When it comes to RDI series the trend slopes have shown a more variable behavior as in RDI-1 zero slope (no trend), in RDI-3 and RDI-6 positive trend slope (increasing trends) and in RDI-9 and RDI-12 negative trend slopes (decreasing trend) have been detected. In comparison as it can be seen from Table 4.1 and Table 4.2 three tests have given similar results in terms of trend type.

Table 4.2. SS test results

	SPI-1	SPI-3	SPI-6	SPI-9	SPI-12
SS	0.00018	0.00037	0.00041	0.00040	0.00043
	SPEI-1	**SPEI-3**	**SPEI-6**	**SPEI-9**	**SPEI-12**
SS	-0.00044	-0.00043	-0.00037	-0.00038	-0.00045
	RDI-1	**RDI-3**	**RDI-6**	**RDI-9**	**RDI-12**
SS	0.00000	0.00004	0.00003	-0.00005	-0.00021
	ZSI-1	**ZSI-3**	**ZSI-6**	**ZSI-9**	**ZSI-12**
SS	0.00003	0.00013	0.00022	0.00032	0.00043
	RAI-1	**RAI-3**	**RAI-6**	**RAI-9**	**RAI-12**
SS	0.00008	0.00023	0.00027	0.00026	0.00028

4.4. Correlation Analysis

In order to examine the correlations between indices Kendall's τ have been used. The results have been presented by Figure 4.3. For a making assessment easier, the correlation values have been illustrated by different colors with the manner of heatmap. As it can be seen from the figure that many times between indices a strong positive correlation have been obtained. For example, the correlation between SPI-1 and RAI-1 is 0.87, SPI-12 and RAI-12 is 0.98, SPI-12 and ZSI-12 0.98, SPEI-12 and RDI-12 is 0.93 and so on.

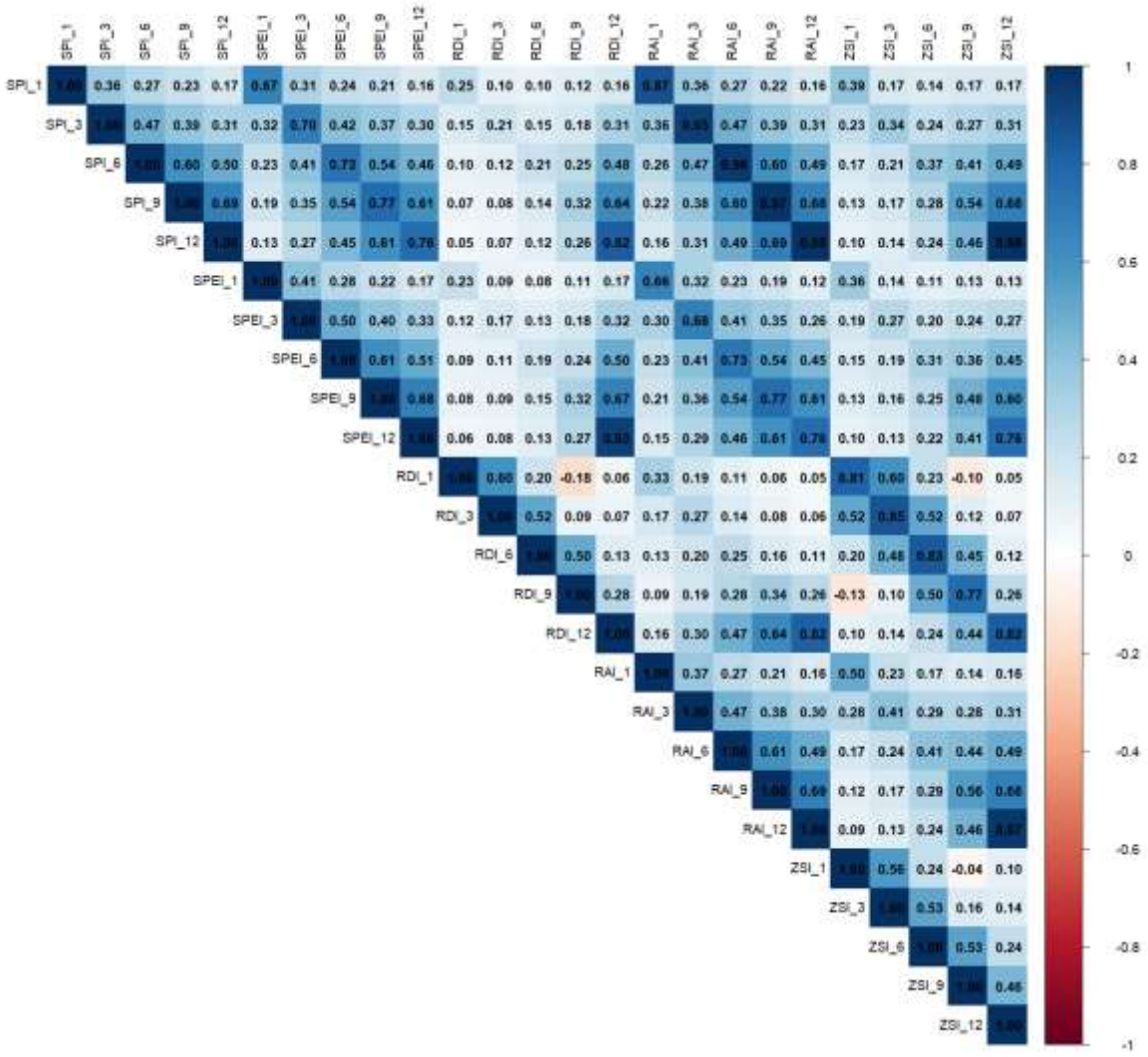

Figure 4.3. Correlation results of indices by Kendall Test

4.5. Discussions

In the study 5 different drought indices have been used to monitor dry and wet events of İzmir regions including trends and correlation. The findings of the study have put forth that normal dry and wet have a superiority among all categories. In the studies of (Yuce & Esit, 2021) have found the similar relationships for Ceyhan Basin Turkiye. In another assessment (Akşan & Bacanlı, 2021) have found that normal dry conditions have superiority upon other dry categories in Southeastern Part of Turkiye. In the study in most of SPI and RAI series significantly increasing trends have been seen. Similarly significant increasing trends in SPI series have been noted by (Benny et al., 2024; Guhathakurta et al., 2017). Similarly significant decreasing trends in SPEI have been noted by (Kamruzzaman et al., 2022) which is also compatible with the findings. The correlation results have shown that strong correlations can be obtained between used indices in different time scales. Similar relationships have been noted by (Katipoğlu et al., 2020; Yuce & Esit, 2021). Therefore, the results of this study are compatible with the findings in the literature.

5. CONCLUSIONS

In this study, using SPI, SPEI, RDI, ZSI and RAI dry and wat conditions of İzmir province have been analyzed for the time scales of 1, 3, 6, 9, 12-month. Possible trends in the time series

of indices have been examined by MK and SR tests considering α=0.01 significance level and trend slopes have been determined by SS test. The correlation between indices have been investigated by Kendall's **τ** have been utilized. Under the light of findings, the following conclusions have been made:

- Based on the time series investigation, many dry (drought) events have been occurred in the past and even near today. Drought indices have captured the common events many times. In all time scales of all indices normal dry and wet categories have the superiority among all categories.

- Trend detection results BY MK and SR tests have shown that while there has been an increasing trend tendency in SPI, ZSI and RAI series, a decreasing trend behavior has been seen in all time series of SPEI. There has been variety of trend types in RDI series. Significant trend conditions have been detected mostly in SPI, SPEI and RAI series. SS test results have shown a similar behavior with MK and SR tests in terms of trend types.

- Correlation results have shown that a strong relationship can be found between indices in different time scales. This also indicates that the indices can get similar outcomes even they have different calculation approach.

- Overall, the study presents significant findings that are expected to be beneficial for local authorities, organizations in the preparing or updating climate action plans and water resources management policy decision making.

ACKNOWLEDGEMENTS

The General Directorate of Meteorology (MGM) of Turkiye is to be acknowledged for providing meteorological data.

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TRANSITIONAL SHELTER STRATEGIES FOR POST-CONFLICT SYRIA: TOWARD A NATIONAL FRAMEWORK FOR RESETTLEMENT AND RECOVERY

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ABSTRACT:

Despite the formal end of armed conflict in Syria following the fall of the Assad regime in December 2024, the country continues to face an acute shelter crisis driven by widespread infrastructure destruction and complex housing, land, and property (HLP) challenges. In northwest Syria, nearly one million internally displaced persons (IDPs) still reside in overcrowded camps and informal settlements. This prolonged displacement places significant pressure on the region's fragile infrastructure, economy, and public services. The continued reliance on tents underscores the urgent need for safe, dignified, and context-appropriate transitional shelter solutions that are both sustainable and scalable. This study is based on a structured literature review of transitional shelter strategies from comparable post-conflict and post-disaster settings around the world. It critically analyzes international frameworks, design models, and policy approaches to identify practices relevant to Syria's urban and rural landscapes. The paper emphasizes the importance of integrating shelter design with recovery goals, sustainability principles, and local environmental and social conditions. The paper concludes by proposing a set of policy recommendations focused on developing a national transitional shelter framework. This framework prioritizes standardized design guidelines, adaptable implementation pathways, and long-term planning integration. It aims to assist humanitarian and governmental actors in replacing tents with safer, more durable interim housing, laying the groundwork for sustainable resettlement and post-war reconstruction.

Keywords: Forced migration, emergency housing, humanitarian architecture, infrastructure strain, and community resilience

INTRODUCTION

Over the past fourteen years, Syria has experienced one of the most protracted and complex humanitarian crises in modern history, driven by war and economic collapse. This crisis has left millions in need of humanitarian assistance, particularly in the northwest of the country. By the end of 2024, an estimated 6.8 million people in northwest Syria required shelter support **[1].** Among these, 2.1 million people were in urgent need of shelter assistance, while approximately 800,000 individuals live in tents **[2]** as emergency shelter situations, which is considered a worldwide symbol of shelter, even though it was not appropriate with long-term shelter.

In this challenging humanitarian context, there was a necessity to adopt a temporary housing policy and more sustainable shelter solutions to address the realities of long-term displacement. In response, the concept of "transitional shelter" was introduced in northwest Syria in 2020 **[3]**. There has been a transition from tents to transitional shelters in northwest Syria over the past four years. While these shelters have significantly improved living conditions for many, they remain far from an adequate solution; they replaced the tents in a partially appropriate manner based on the available resources.

This initiative represented a significant shift from the prolonged reliance on temporary shelter options traditionally employed by the shelter sector in Syria. Its primary aim was to provide safety, dignity, and protection for internally displaced people (IDPs) affected by conflict and displacement. However, while many local and international humanitarian organizations contributed to the proliferation of various models of transitional shelters in northwest Syria, these efforts often lacked standardized design and implementation criteria. Additionally, the exclusion of affected populations from decision-making processes reduced the overall impact of transitional shelters in facilitating the transition of IDP sites toward recovery.

Even after the fall of the Assad regime, Syria continues to face a complex humanitarian crisis. Massive displacements caused by escalations in the conflict for more than 13 years, coupled with inadequate IDP sites and extreme living conditions, particularly during harsh winters, have exacerbated the crisis, making it a significant humanitarian concern. Additionally, the housing crisis remains a critical challenge for the new government, especially in facilitating the return of internally displaced persons (IDPs) and refugees from neighboring countries.

Therefore, this study explores a literature review of transitional shelter strategies from comparable post-conflict and post-disaster settings around the world. It critically analyzes international frameworks, design models, and policy approaches to identify practices relevant to Syria's urban and rural landscapes. Then, the study analyzes the 3 different types of transitional shelter solutions that were adopted by international agencies, local organizations, and community-led initiatives in Syria.

In the same regard, this study aims to examine the transitional shelter models applied in both internationally, and locally – in Syria – to identify the most context-appropriate, sustainable, and scalable solution to support the internally displaced people.

The analysis also seeks to support developing a national transitional shelter framework that plays a fundamental role in the reconstruction of the post-conflict Syria.

METHODOLOGY

Initially, the paper begins with a comprehensive literature review to establish a conceptual framework for emergency shelters, encompassing a wide range of theoretical approaches related to post-disaster shelter provision. This is followed by an explanation of the concept of

transitional shelters implemented in northwest Syria, detailing the types of transitional shelters utilized, along with their advantages and disadvantages, as informed by the literature review. The sources reviewed include academic books, journal articles, conference papers, and 'secondary literature' from humanitarian organizations and UN Clusters.

Then, the study conducts a targeted literature review and a content analysis of the global bibliography on transitional shelters in post-war or post-disaster contexts, focusing on similar international experiences. An inductive research approach is employed to develop an evidence base and to understand shelter strategies adopted in comparable international settings.

Finally, the findings and data analysis will provide a comparative assessment aimed at identifying the most effective and adaptable solutions for transformable shelter designs. Based on the final data analysis and findings, a comparative approach will be adopted to find the best solution for a transformable shelter.

LITERATURE REVIEW

Shelter after Disaster Definition:

The destruction of homes, whether through conflict, displacement, or natural disasters, is one of the most visible and devastating consequences of crises. Providing adequate shelter in the aftermath of such events is not only essential for saving lives but also critical for supporting livelihoods, health, education, security, and family stability. According to UN/OCHA/ESB (2006), adequate shelter constitutes the “immediate environment for all aspects of family life,” offering protection from the elements, secure tenure, safety, access to clean water and sanitation, and proximity to employment, education, and healthcare services **[4]**.

Importantly, "shelter after disaster" is understood not merely as a physical structure but as a dynamic process that involves progression from emergency accommodation to more durable and sustainable housing solutions **[5].** As such, shelter interventions are typically divided into emergency and transitional phases, each requiring different approaches, stakeholders, and timelines that may span several years.

Over the past two decades, those involved in shelter provision have not reached a consensus on a universal definition of adequate shelter, resulting in varied terminology describing it. According to Corsellis and Vitale (2005), shelter is described as a livable, covered space that offers a secure and healthy environment, ensuring privacy and dignity for its occupants **[5]**. Similarly, the Global Protection Cluster Working Group notes that when humanitarian organizations mention shelter, they typically refer to a livable, covered space that provides a secure and healthy environment with privacy and dignity **[6].**

In constructing the shelter framework, we identified that not everyone agrees on a staged approach to post-disaster shelter. The Shelter Center is intended to be adopted as a “three-stage recovery” model of shelter. These stages begin with the first-response emergency shelter, followed by medium-term transitional solutions, and finally permanent housing. While some experts have advocated for a two-stage model, removing the need for transitional shelter **[7].** The figure depicts both the three-phase and two-phase models of shelter response, which are widely recognized within the shelter sector.

Emergency shelter refers to immediate, short-term housing provided in the aftermath of a disaster or conflict to ensure the survival and protection of displaced individuals or households. These shelters are intended to offer basic protection from the elements, privacy, and security, while meeting minimum humanitarian standards until more durable solutions become available.

The UNHCR Emergency Handbook (2022) defines emergency shelter as "the provision of temporary protection from the climate, often in the form of tents or other rapidly deployable structures, to meet the basic shelter needs of displaced populations" **[8]**. Corsellis and Vitale (2005) stated that "shelter after disaster is a process that begins with emergency shelter, typically provided in the form of tents, plastic sheeting, or host family arrangements, and gradually transitions to more sustainable and permanent housing" **[5]**. The necessity for such temporary aid is expected to remain a key component of emergency response efforts, particularly in contexts involving large, displaced populations and harsh environmental conditions **[9]**.

Transitional Shelter:

The concept of transitional shelter has emerged as one of the key shelter response options currently in use. This approach was introduced by staff from the Shelter Centre, seconded by the UK's Department for International Development (DFID), to the United Nations High Commissioner for Refugees (UNHCR) in 2005, in the aftermath of the Indian Ocean tsunami in December 2004 **[10]**. During the transitional phase, displaced families may find temporary shelter with host families, in camps, collective centers, or by self-settling in existing buildings. However, these arrangements are not always suitable for all families throughout the entire reconstruction period. Thus, the transitional shelter concept aims to provide safe, adaptable housing while long-term reconstruction efforts are underway **[11]**.

The Shelter Centre defines transitional settlement as "settlement and shelter resulting from conflict and natural disasters, ranging from emergency response to durable solutions" **[5]**. According to Brogden and Liz (2021), transitional shelter is understood as a gradual recovery process that enables families affected by disasters and conflicts to retain flexibility in their recovery pathway **[7]**. These shelters are designed to be: (1) upgradable into permanent homes, (2) repurposed for alternative uses, (3) relocatable from temporary to permanent sites, (4) sold to generate income, or (5) recycled for reconstruction purposes **[7]**.

Importantly, the evolving definition of transitional shelter excludes prefabricated final shelters and core shelters—the latter being semi-permanent structures designed to be expanded but not reused, relocated, or recycled **[7]**.

In summary, emergency shelter refers to immediate, short-term housing provided in the aftermath of a disaster or conflict to ensure the safety and survival of displaced individuals. It typically offers minimal protection, privacy, and security, and is used for days to a few months. These shelters, often prefabricated and rapidly deployable (e.g., tents, tarpaulins, or communal buildings), are generally not tailored to local cultural or climatic conditions. By contrast, transitional shelter acts as a medium-term solution, bridging the gap between emergency and permanent housing. It is more durable and context-appropriate, supporting recovery through local materials, labor, and adaptability. Soti, Bimal, and Dimmy (2012) stated that emergency shelter response primarily addresses protection and relief during and immediately following a disaster. In contrast, the transitional shelter approach integrates disaster response with the immediate transition to reconstruction, recovery, and sustainable development **[12]**. These shelters may include timber-framed units, rehabilitated houses, or homes shared with host families. As Corsellis and Vitale (2005) note, "Transitional shelter is intended to support the process of recovery and can be upgraded, reused, or relocated as part of a longer-term strategy" **[5].**

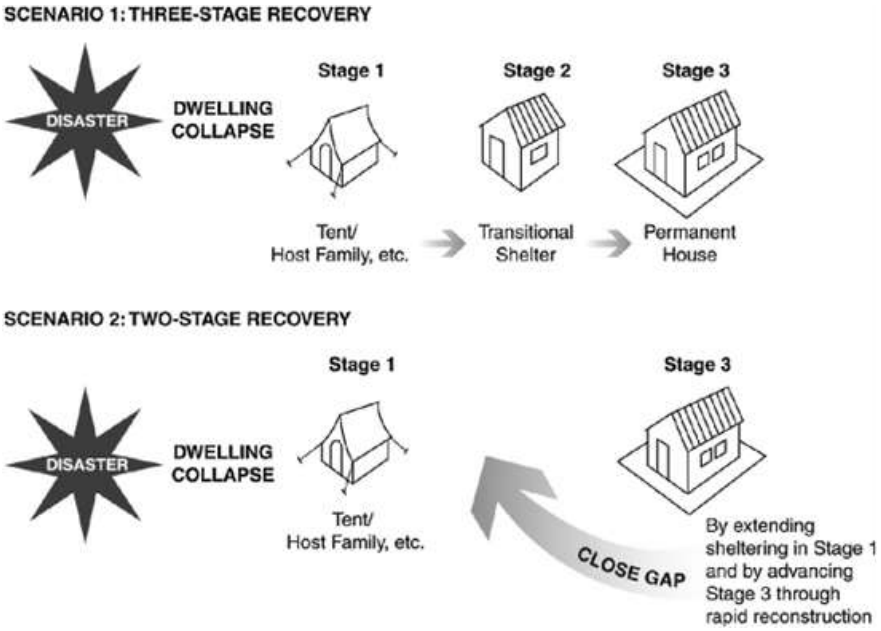

Figure 1: Transitional shelter scenarios **[7]**

Figure 1 illustrates two commonly adopted recovery pathways following a disaster: a three-stage approach and a two-stage alternative. In the first scenario, displaced families move from emergency shelters like tents into a transitional shelter before eventually reaching a permanent home. The second scenario bypasses the transitional phase entirely by either extending the emergency shelter's function or accelerating permanent reconstruction. Including this figure helps clarify an important discussion within shelter literature: should transitional shelters serve as a distinct phase, or can they be replaced with more efficient long-term solutions? In this paper, the figure serves to position transitional shelter within that broader strategic debate, especially as it applies to the Syrian context.

International Case Studies Review

Transitional shelter is considered an essential part in supporting post-disaster recovery, serving as a link between emergency relief and permanent housing solutions **[8] [9].** This section provides a literature review, examining prominent case studies highlighting the complexities of transitional shelter models and best practices in their design and implementation. Analyzing these real-world examples allows us to identify challenges and lessons learned, which can inform future shelter strategies in disaster-affected areas.

Transitional shelter alternatives differ from one country to another and are influenced by various circumstances; however, a consistent aspect is that individuals who have been displaced face restricted choices. They have the option to stay at their former residences, but these are often compromised and either uninhabitable or partially livable. In this section, several shelter response models are analyzed. Since there are numerous types of shelter models available, the reference models were chosen based on the following key criteria:

1. The transnational phase is the target phase.

2. Local Materials used in shelter construction: It is investigated whether the material is sourced locally or can only be sourced internationally. Material sources have a huge impact on the local economy, price, and delivery times.

3. Durability: defines the ability of shelter to remain safe, functional, and habitable for the intended duration of use.

Model 1: Container as Transitional Shelter

A review of literature indicated that containers are utilized as emergency shelters and temporary housing following disasters in countless situations using certain standards to meet the urgent need after disasters **[13] [14]**. For instance, it was used in Greece for resettlement refugees in camps in 2019 **[15]** and used in Türkiye after Kahramanmaraş earthquakes in 2023 **[14]**. The policy approach of provisioning this model for shelter offers a more environmentally sustainable construction method by reducing construction time, minimizing waste, and decreasing the overall on-site workload.

To address the diverse needs of disaster victims and ensure compliance with internationally recognized transitional shelter standards, numerous prototypes and proposed containers models have been developed. These initiatives seek to improve the quality of humanitarian response, increase the efficiency of field interventions, and better align with the social, cultural, and climatic characteristics of affected population **[14]**. Moreover, it depends on the suppliers for containers. In the case of Athena's camps, the container shelter had been imported from China by the K-Home company **[15]**. While the containers that were used after the earthquake in Türkiye were manufactured locally in the country **[14].**

Container shelters as shown in figure 2 are generally based on a rigid steel frame combined with insulated wall and roof panels, forming a simple rectilinear "box" that is easy to transport, stack, and arrange in different site configurations. The emphasis is on a modular, repeatable form that can be rapidly deployed, connected to basic services, and later adapted or combined to create larger living or community spaces. In terms of durability, container shelters are designed to fulfil the core requirements of transitional shelter, as they can be upgraded, reused, relocated, resold, and eventually recycled throughout their life cycle **[15].**

Even though the containers are transported packaged and are assembled on-site to improve space efficiency, it needs skilled workers to modify the containers, such as cutting, welding, and connecting.



Figure 2: The structure and Design of a Container Shelter **[16]**

Model 2: UNHCR Refugee Housing Unit (RHU)

In 2015, the Swedish company IKEA lunched a partnership with Better Shelter Foundation to develop and improved a shelter solution that provides greater dignity and supports the protection of millions displaced people and refugees around the world **[15]**. In addition, the Shelter is evaluated carefully by UNHCR.

One of the disadvantages of the Better Shelter is that the shelter is produced completely outside of the affected country. As all production happens currently almost entirely in Northern Europe, this could affect the locality of the shelter.

The model shown in figure 3 relies on a lightweight structural frame combined with modular wall and roof panels that can be easily transported and assembled in the field. Its enclosure system is based on durable, weather-resistant composite materials that offer a balance between strength, insulation, and simplicity of installation. The shelter's components are designed to interlock through a standardized connection system, allowing families or field teams to assemble the unit without heavy equipment.

To ensure stability in diverse site conditions, the design incorporates a basic anchoring approach that secures the structure against wind loads and shifting ground. In terms of durability, this model fits very well with the idea of upgrading existing transitional shelters to more permanent shelters. The shelter is expected to serve between 1.5 to 5 years depending on the maintenance, although the metal structure itself has an expected lifespan of more than ten years.

RHUs have been deployed across a wide range of humanitarian settings. UNHCR and partner agencies have introduced RHUs in major refugee-hosting countries, including Jordan, Iraq, Lebanon, and pilot sites in Türkiye, as well as in camps across Ethiopia, Kenya, Uganda, and Mauritania. They were also widely used during the 2015–2016 refugee influx in Greece and in disaster or displacement responses in Nepal, Bangladesh, and Colombia. These diverse applications highlight the RHU's role as a globally recognized transitional shelter solution endorsed by UNHCR **[15][16]**



Figure 3: Refugees Housing Units RHU **[17]**



Figure 4: Refugees Housing Units RHU **[17]**

Model 3: Community led Transitional Shelter

Engaging local communities is essential for the success of transitional shelter programs. Community members provide insights into cultural norms, preferences, and specific needs, ensuring that shelters are acceptable and functional for the intended users. The participatory approach of transitional shelter provision, underpinned by effective coordination, ensures that displaced populations receive timely, appropriate, and sustainable housing solutions **[5]**. Analyzing case studies from another disasters, such as the 2010 Haiti earthquake provides valuable insights into the best practices of implementing transitional shelter programs in collaboration with the local communities. This case study highlights the importance of stakeholder coordination, cultural considerations, and adaptability to local contexts in ensuring the effectiveness and sustainability of shelter interventions.

The 2010 Haiti earthquake, which struck on January 12, resulted in catastrophic destruction, leaving over 1.5 million people homeless and causing extensive damage to infrastructure across the country. In response to this humanitarian crisis, transitional shelter programs were rapidly implemented to provide displaced populations with safer, more durable alternatives to emergency tents and tarpaulins.

Organizations such as the International Organization for Migration (IOM), Habitat for Humanity, and The Salvation Army played pivotal roles in these efforts. The IOM alone provided transitional shelters to over 10,000 families, aiming to replace vulnerable tent settlements with more stable housing solutions. These shelters were designed to be upgradeable, relocatable, and constructed using local materials and labor, thereby supporting both immediate needs and long-term recovery efforts **[18].**

Habitat for Humanity focused on building recyclable and upgradeable shelters, with a goal to serve 50,000 families over five years. By the end of 2010, they had constructed over 1,000 such shelters and distributed more than 21,000 emergency shelter kits. Their approach emphasized community involvement, with local leaders participating in identifying vulnerable families and setting up rebuilding priorities **[19]**.

The Salvation Army completed the construction of 600 transitional shelters in Jacmel, Haiti, by July 2010. Their program not only provided housing but also employed over 400 Haitians as carpenters and construction crew members, integrating livelihood support into the recovery process **[20]**.

Despite these efforts, the transitional shelter programs faced significant challenges. Land tenure issues, debris removal, and coordination among various stakeholders often delayed construction and hindered the effectiveness of the response. Additionally, the scale of displacement and the urgency of the situation required **[18]**.

In conclusion, the transitional shelter initiatives following the 2010 Haiti earthquake provided critical relief to thousands of displaced families and contributed to the broader recovery efforts. These programs underscored the importance of community involvement, adaptability, and coordination among humanitarian actors. However, they also highlighted the complexities and challenges inherent in post-disaster shelter provision, offering valuable lessons for future responses in similar contexts. Rapid action, sometimes at the expense of long-term planning and sustainability.



Figure 5: Model of Haiti Earthquake Shelter **[21]**



Figure 6: Model of Haiti Earthquake Shelter **[21]**

Syria Transnational Shelter Models

For long years, the emergency shelter strategy following the conflict in Syria adopted short-term shelter interventions, which required substantial future funding commitments as tents rapidly deteriorate and must be replaced. Therefore, there was an urgent need for a more systematic approach to improving shelter and living conditions in northwest Syria. Therefore, in 2022, the Shelter and Nonfood Items Cluster introduced the Dignified Shelter & Living Conditions framework as a more appropriate approach for protracted displacement, functioning as a transitional shelter model designed to reduce reliance on short-term assistance cycles and increase resilience **[22]**. In the context of emergency management, diversifying the range of transitional shelter solutions is considered highly beneficial. Thus, a combination of options should be explored, complementing the production of prefabricated units for temporary settlements.

Model 1: International Organization Transitional Shelter Model: Model 1: Prefabricated Shelter Unit

Ranging from converted shipping containers to flat-pack modular kits, prefabricated units represent the most durable transitional shelter option currently deployed in Syria. The most common example is the caravan unit (approximately 4×5 m, 20–21 m²) as shown in figure 7, extensively used in northern Idleb and expanded after the 2023 earthquakes in Aleppo and Idlib. These steel-frame, insulated-panel shelters offer strong resistance to rain, snow, and wind, providing a durability lifespan of 5–10 years, particularly when winterization kits are added **[17]**

However, the model relies almost entirely on imported industrial materials and external manufacturing, offering minimal engagement of local labor or local construction markets. Although highly effective in rapid deployment and providing significantly better protection than tents, prefabricated units remain the most expensive transitional shelter model in Syria due to high procurement, transportation, and installation costs. Their scalability has therefore been limited, with only around 4% of shelters in assessed NWS camps classified as factory-made units **[18]**. Overall, this model offers the highest durability and fastest deployment but the lowest cost efficiency and weakest integration with local materials and labor systems.



Figure 7: Prefabricated Shelter in Syria **[23]**

Model 2: Local Organization Transitional Shelter Model: Concrete Block Shelter Unit

Concrete-block shelters—commonly implemented by Syrian NGOs such as ATAA—constitute one of the most context-appropriate transitional shelter solutions in northwest Syria. These one-room masonry structures, often measuring 45–65 m² in large-scale settlements such as the 4,500-unit project in Jarablus, provide durable, weather-resistant housing for displaced families transitioning out of tents. Their masonry walls and lightweight metal roofing offer long-term durability (10–25 years), improved insulation, and better flood protection when constructed on elevated plinths with proper drainage **[19]**

Unlike prefabricated units, this model depends heavily on locally available materials such as concrete blocks, cement, gravel, and metal sheets as clearly reflected in figure 8and local construction labor, which supports livelihoods and strengthens local markets. Humanitarian shelter designs often integrate Sphere standards regarding floor area, ventilation, and climate considerations **[20].**While more costly than tents, concrete-block shelters are significantly more cost-efficient than prefabricated units, and their potential for incremental upgrading makes

them one of the most scalable and economically sustainable transitional shelter solutions in a protracted displacement context.



Figure 8: Concrete Shelter in Syria **[23]**



Figure 9: Concrete Shelter in Syria – By Author

Model 3:Community-Led Transitional Shelter Model : Mud-Brick Shelters

Mud-brick shelters draw from traditional Syrian rural architecture, using sun-dried earthen blocks mixed with straw to form thick insulating walls, typically topped with timber or metal roofing and earth-based plaster. These 4×4 m units (approximately 16 m²) shown in figure 10 have been piloted in several parts of Idlib through community groups and cash-for-work programs, enabling displaced families to participate in brick production and construction. Although less durable than concrete shelters, mud-brick units offer moderate durability (5–8 years) when maintained and protected from heavy rain through raised foundations, plastering, and roof overhangs **[21]**.

This model excels in the use of local materials such as soil, straw, and earth plaster, making it highly sustainable and culturally familiar. Its cost efficiency is exceptionally high, as materials are inexpensive and labor is community-based, often requiring minimal external funding. Academic assessments highlight the environmental advantages, cultural acceptance, and livelihood-generation potential of earthen construction **[22]**. Overall, mud-brick shelters provide the lowest-cost and most locally integrated transitional solution, though with durability limitations that make them suitable primarily for rural and moderate-term displacement scenarios.



Figure 10: Mud Brick Shelter in Syria **[21]**

RESULTS AND CONCLUSION

The findings of this study demonstrate that transitional shelter is not merely a temporary housing option, but a pivotal strategic component for stabilizing post-conflict Syria and facilitating the shift from protracted displacement toward organized resettlement and recovery. The comparative analysis of global case studies and Syrian shelter models reveals that no single approach can adequately address the complex humanitarian and housing needs of northwest Syria. Instead, a diversified shelter ecosystem is required one that balances durability, cultural relevance, cost efficiency, and scalability.

International prefabricated units offer the highest levels of durability and the fastest deployment, particularly in the aftermath of major disasters such as the 2023 earthquakes. These units are uniquely versatile, as they can be reassembled and repurposed into community centers, temporary schools, children's libraries, or other educational spaces according to local needs. With appropriate structural enhancements, they can also be upgraded or converted into permanent housing, making them a flexible option that bridges transitional shelter and long-term accommodation. However, their dependence on imported materials and their high overall costs significantly limit their potential for large-scale implementation in Syria.

In contrast, concrete-block shelters implemented by local organizations represent a more sustainable and economically viable model. These shelters rely on local materials and labor, thereby strengthening community resilience and supporting early economic recovery, while offering long-term durability and compatibility with Sphere standards and local climatic conditions. Community-led mud-brick shelters present a highly cost-efficient, culturally rooted, and environmentally sustainable option, especially in rural areas. Their participatory construction processes generate livelihood opportunities for displaced populations, although their durability remains moderate compared to concrete units.

Collectively, these models underline the urgent need for a national transitional shelter framework that moves beyond fragmented, project-based interventions. Such a framework must incorporate standardized design guidelines, climate-sensitive typologies for both urban and rural contexts, and clear implementation pathways that align humanitarian actions with national reconstruction policies. Housing, Land, and Property (HLP) considerations should be embedded to ensure tenure security and enable families to gradually upgrade transitional units into permanent homes. Community participation must also be institutionalized as a central pillar in design, planning, and governance.

This study concludes that transitional shelter when approached as an adaptable, integrated system can serve as a cornerstone of Syria's post-conflict housing strategy. By leveraging diverse shelter models, aligning them with global best practices, and anchoring them in local materials and community capacities, Syria can move beyond tent-based settlements and establish dignified, safe, and scalable housing solutions that pave the way for sustainable resettlement and reconstruction.

Looking ahead, future research can build upon the findings of this paper by developing a more detailed cost-benefit analysis of transitional shelter models in different Syrian regions. Additionally, longitudinal field studies could assess the long-term social and economic impacts of each shelter type on displaced populations. Expanding this framework to include community feedback mechanisms, climate adaptation considerations, and gender-sensitive design would further enhance the relevance and applicability of shelter strategies in post-conflict settings.

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COMPARISON of RAPID ASSESSMENT METHODS FOR RESIDENTIAL BUILDINGS in BINGOL PROVINCE by USING ARTIFICIAL NEURAL NETWORKS

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ÖZET

Hızlı nüfus artışı ve artan kentleşme oranları, deprem gibi doğal afetlerin oluşturduğu riskleri artırmaktadır. Özellikle Türkiye gibi aktif fay hatları üzerinde bulunan ülkelerde, mevcut bina stokunun sismik performansının belirlenmesi hayati önem taşımaktadır. Ancak, tüm binaları ayrıntılı analiz yöntemleriyle tek tek incelemek, zaman ve maliyet açısından sürdürülebilir değildir. Bu çalışma, yüksek sismik risk altındaki Bingöl ilindeki konut binalarının sismik performansını belirlemek için kullanılan Hızlı Görsel Tarama (RVS) yöntemlerinin etkinliğini karşılaştırmalı olarak incelemektedir. Çalışma kapsamında, Türkiye'nin Riskli Yapıların Tespiti Yönetmeliği (RBTY-2019), ABD merkezli FEMA-P154 ve Hindistan merkezli IITK-GSDMA yöntemleri ile bu çalışma kapsamında geliştirilen Yapay Sinir Ağı (ANN) tabanlı model kullanılmıştır. Analizlerde, 2003 Bingöl depremi sonrasında hasar değerlendirmesi yapılan 35 gerçek binadan elde edilen veriler referans (yer gerçeği) olarak kullanılmıştır. Çalışmanın benzersiz bir katkısı olarak, RBTY-2019 sonuçlarını bölgesel önceliklendirmede kullanmak için yeni bir "Ölçeklendirme Fonksiyonu" geliştirilmiştir. Bulgular, FEMA-P154 yönteminin ekonomik olmadığını, %48,6 doğrulukla oldukça güvenli bir seviyede kaldığını gösterirken, IITK-GSDMA yöntemi %62,9 ve ölçeklendirilmiş RBTY-2019 yöntemi %71,4 tutarlılık sağladı. Geliştirilen ANN modeli en yüksek tahmin başarısını sergiledi ve hızlı değerlendirme süreçlerinde yapay zeka kullanımının potansiyelini ortaya koymuştur.

Anahtar Kelimeler: Hızlı Görsel Tarama, Sismik Risk, Bingöl, Yapay Sinir Ağları, Sismik Performans

GİRİŞ

Türkiye, jeolojik yapısı ve tektonik konumu itibariyle dünyanın en aktif deprem kuşaklarından biri olan Alp-Himalaya deprem kuşağı üzerinde yer almaktadır. Özellikle Bingöl ili, Kuzey Anadolu Fay Zonu (KAFZ) ve Doğu Anadolu Fay Zonu (DAFZ) gibi iki büyük fay sisteminin kesişim noktası olan Karlıova Üçlü Eklemi yakınında bulunması sebebiyle sismik riskin en yüksek olduğu bölgelerden biridir (Akbayram et al., 2022).

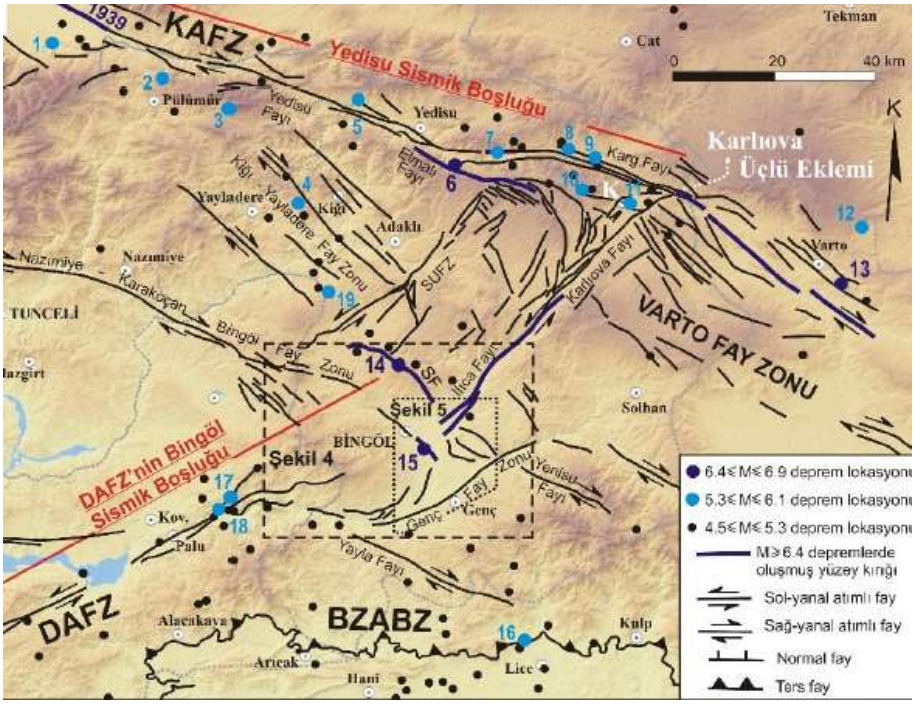

Figure 1. *Bingöl'ü kuşatan faylar ve sismik boşluklar (Akbayram et al., 2022)*

Bölgedeki hızlı nüfus artışı ve geçmişteki kontrolsüz yapılaşma pratikleri, "standart dışı" olarak nitelendirilebilecek ve deprem güvenliği açısından risk taşıyan bir yapı stokunun oluşmasına neden olmuştur.

Olası bir deprem senaryosunda can ve mal kaybını en aza indirmek için mevcut yapı stokunun deprem performansının belirlenmesi ve riskli yapıların tespit edilmesi afet yönetiminin en kritik aşamasıdır (AFAD, 2018). Ancak, bir şehirdeki binlerce binanın her birinin ayrıntılı yapısal analiz yöntemleri ile incelenmesi hem zaman hem de maliyet açısından mümkün değildir. Bu kısıtlar, yapıları "riskli", "muğlak" veya "güvenli" olarak hızlıca sınıflandırabilen ve önceliklendirebilen Hızlı Görsel Tarama (HGT) yöntemlerine olan ihtiyacı artırmıştır (Sucuoğlu et al., 2007).

Bu çalışmanın temel amacı; ulusal yöntemimiz olan RBTY-2019 ile uluslararası literatürde yaygın olarak kullanılan FEMA-P154 ve IITK-GSDMA yöntemlerinin Bingöl özelindeki doğruluk oranlarını karşılaştırmaktır (FEMA-P154, 2017; RBTY, 2019; Sinha & Goyal, 2004). Karşılaştırma için 2003 Bingöl depreminde hasar görmüş ve performansları ***"gerçek hayat verisi"*** olarak kaydedilmiş binalar kullanılmıştır.

Ayrıca çalışma kapsamında, geleneksel, kural tabanlı ***(rule-based)*** yöntemlerin eksikliklerini gidermek ve parametreler arasındaki karmaşık ilişkileri ***(non-lineerite)*** çözebilmek amacıyla Yapay Sinir Ağları (YSA) tabanlı yeni bir tahmin modeli önerilmiş ve performansı diğer yöntemlerle kıyaslanmıştır (Varolgüneş, 2023).

MATERYAL VE YÖNTEM

Bu çalışmada, Bingöl ilindeki mevcut betonarme yapı stokunu temsil eden bir veri seti kullanılarak, üç farklı konvansiyonel HGT yöntemi ve bir yapay zeka modeli (YSA) uygulanmıştır.

Çalışma Alanı ve Veri Seti

Çalışma alanı olarak, 1 Mayıs 2003 tarihinde meydana gelen ve büyük yıkıma yol açan Bingöl Depremi'nden etkilenen bölge seçilmiştir. Analizlerde kullanılan veri seti, deprem sonrasında Orta Doğu Teknik Üniversitesi (ODTÜ) bünyesindeki SERU (Structural Engineering Research Unit) ekipleri tarafından yerinde incelenen ve hasar durumları detaylı olarak raporlanan 35 adet betonarme binadan oluşmaktadır . İncelenen binalar genellikle 2-5 katlı olup betonarme çerçeve sistemine sahiptir (SERU, 2003).

Referans kabul edilen gerçek hasar dağılımı (Ground Truth) şu şekildedir: %31 Hasarsız, %29 Hafif Hasarlı, %17 Orta Hasarlı, %20 İleri Hasarlı ve %3 Göçme durumu. Bu dağılım, yöntemlerin doğruluk analizinde ***"hedef çıktı"*** olarak kullanılmıştır.

İncelenen Hızlı Değerlendirme Yöntemleri

Çalışmada aşağıdaki yöntemler uygulanmıştır:

RBTY-2019 (Türkiye): 6306 sayılı "Afet Riski Altındaki Alanların Dönüştürülmesi Hakkında Kanun" kapsamında kullanılan, binaların bölgesel risk dağılımını belirlemeyi amaçlayan, yapısal sistem puanı ve olumsuzluk parametrelerine dayalı ulusal yöntemdir (RBTY, 2019).

FEMA-P154 (ABD): Federal Acil Durum Yönetim Kurumu tarafından geliştirilen, "sokak taraması" esasına dayanan ve binayı temel sismik tehlike puanından başlayarak çeşitli olumsuzluk katsayıları ile puanlayan yöntemdir (FEMA-P154, 2017).

IITK-GSDMA (Hindistan): FEMA tabanlı olup Hindistan'ın yerel inşaat pratiklerine ve malzeme özelliklerine göre uyarlanmış versiyondur (Sinha & Goyal, 2004).

YSA Modeli (Önerilen Yöntem): ***MATLAB*** ortamında geliştirilen, çok katmanlı, ileri beslemeli ve geri yayılımlı ***(feed-forward backpropagation)*** bir yapay sinir ağı modelidir. Modelde kat sayısı, yumuşak kat, kısa kolon, ağır çıkma, plan düzensizliği, zemin sınıfı ve yapı nizamı gibi parametreler ***"girdi katmanı"***, gerçek hasar durumu ise ***"çıktı katmanı"*** olarak tanımlanmıştır. Eğitim için ***Levenberg-Marquardt*** optimizasyon algoritması ***(trainlm)*** kullanılmıştır.

RBTY-2019 İçin Geliştirilen Ölçeklendirme Fonksiyonu

RBTY-2019 yönetmeliği, binaları temel olarak risk önceliğine göre sıralamakta ancak sayısal puanları doğrudan bir "hasar seviyesine" (Örn: Orta Hasar, Ağır Hasar) dönüştürmemektedir. Bu çalışmada, RBTY-2019'dan elde edilen Performans Puanlarını (PP), gerçek hasar verileriyle (SERU 2003) ilişkilendirerek 5 farklı hasar seviyesine dönüştüren özgün bir Yerel Ölçek Fonksiyonu (LSF) geliştirilmiştir.

Bu fonksiyon sayesinde RBTY sonuçları, diğer yöntemlerle ve gerçek hasar verileriyle karşılaştırılabilir hale getirilmiştir. Geliştirilen ölçeklendirme aralıkları Tablo 1'de sunulmuştur.

Table 1. *RBTY-2019 Ölçeklendirme Fonksiyonu*

		PP	≤	-10	Göçme Bölgesi	1
-10	<	PP	≤	11	İleri Hasar	2
11	<	PP	≤	45	Orta Hasar	3
45	<	PP	≤	81	Az Hasar	4
81	<	PP			Hasarsız	5

BULGULAR

Analizler sonucunda, her bir bina için yöntemlerin ürettiği hasar tahminleri, 2003 depreminde gerçekleşen hasar durumlarıyla karşılaştırılmıştır.

FEMA-P154 Sonuçları

Yöntemin Bingöl verileriyle tutarlılık oranı %48,6 olarak hesaplanmıştır. FEMA yöntemi, binaların çok büyük bir kısmını ***"potansiyel riskli"*** olarak etiketlemiş ve aşırı güvenli tarafta kalmıştır. Bu durum, incelenen binaların neredeyse tamamı için ***"Ayrıntılı Analiz"*** gerekliliği doğurduğundan, yöntemin hızlı tarama ve eleme amacına Bingöl özelinde tam hizmet etmediği görülmüştür.

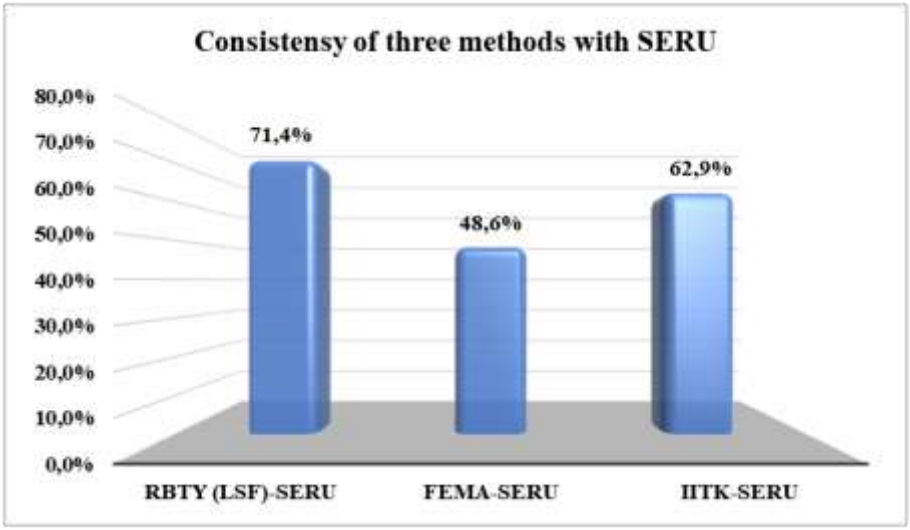

Figure 2*. Consistency of 3 methods with SERU*

IITK-GSDMA Sonuçları

Hindistan yönetmeliği, FEMA P154'e kıyasla daha iyi bir performans sergilemiş ve %62,9 tutarlılık oranına ulaşmıştır. Ancak bazı kritik binalarda (örneğin göçme riski olan) yanıltıcı güvenli sonuçlar verebildiği gözlemlenmiştir.

RBTY-2019 (Ölçeklendirilmiş) Sonuçları

Bu çalışma kapsamında geliştirilen ölçeklendirme fonksiyonu ile uygulanan ulusal yöntemimiz, %71,4 tutarlılık oranı ile konvansiyonel yöntemler arasında en yüksek başarıyı göstermiştir. Yöntem, özellikle "riskli" ve "güvenli" yapıları ayırmada diğer yöntemlere göre daha dengeli bir dağılım sergilemiştir.

YSA Modeli Sonuçları

Geliştirilen Yapay Sinir Ağı modeli, veri seti üzerinde eğitildiğinde parametreler arasındaki non-lineer ilişkileri başarıyla öğrenmiştir. Test veri seti üzerinde yapılan doğrulama analizlerinde YSA modeli, referans hasar verileriyle %100'e varan yüksek bir uyum göstermiştir.

Aşağıdaki grafikte yöntemlerin tutarlılık oranlarının karşılaştırması verilmiştir.

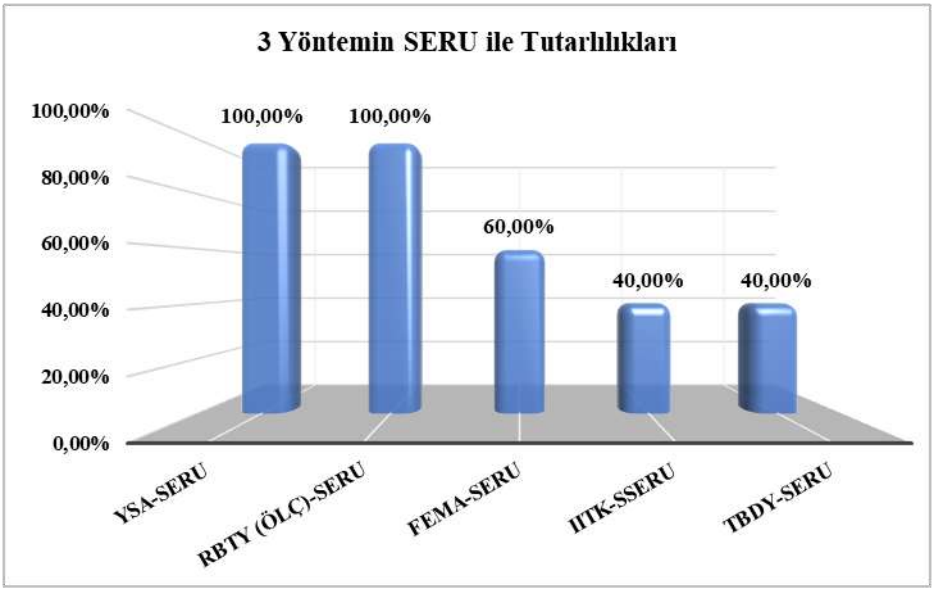

***Figure 3**. HGT Yöntemlerinin ve YSA Modelinin Doğruluk Oranları*

TARTIŞMA VE SONUÇ

Bu çalışma, Bingöl ilindeki mevcut betonarme konut stoku için hızlı değerlendirme yöntemlerinin güvenilirliğini ortaya koymuştur. Elde edilen sonuçlar ışığında şu değerlendirmeler yapılabilir:

Yöntemlerin Yerelliği

FEMA-P154 gibi uluslararası yöntemler, geliştirildikleri ülkenin (ABD) yapı karakteristiğine ve güvenlik katsayılarına göre kalibre edildiğinden, Türkiye gibi farklı yapı kültürüne sahip ülkelerde doğrudan uygulandığında aşırı muhafazakâr sonuçlar vermektedir. Bu durum, kaynakların verimsiz kullanılmasına yol açabilir.

Ulusal Yöntemin Başarısı:

RBTY-2019, Türkiye'deki yapı stokunun karakteristik özelliklerini (yumuşak kat, ağır çıkma vb.) daha iyi parametrize ettiği için, bu çalışmada önerilen "Ölçeklendirme Fonksiyonu" ile entegre edildiğinde bölgesel taramalar için en güvenilir konvansiyonel yöntem olarak öne çıkmaktadır.

Yapay Zekanın Gücü: YSA modeli, kural tabanlı yöntemlerin aksine, veriler arasındaki karmaşık örüntüleri öğrenebildiği için en yüksek tahmin başarısını göstermiştir. Gelecekte, daha büyük veri setleriyle (Örn: 2020 Elazığ, 2023 Kahramanmaraş depremleri verileriyle) eğitilecek YSA modelleri, şehir ölçeğindeki risk haritalarının çıkarılmasında en güçlü araç olacaktır.

Sonuç olarak; Bingöl ve benzeri yüksek sismik riske sahip bölgelerde yapılacak kentsel dönüşüm çalışmalarında, önceliklendirme aracı olarak Ölçeklendirilmiş RBTY-2019 yöntemi

veya eğitilmiş YSA modellerinin kullanılması, karar vericilere zaman ve maliyet açısından büyük avantaj sağlayacaktır.

ACKNOWLEDGEMENT

Bu çalışma Dicle Üniversitesi iş birliği ile yürütülen doktora tez çalışmasından üretilmiştir.

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TÜRKİYE'DE DEPREM DIŞI PROGRESİF YAPI GÖÇMELERİ: BİRİKİMLİ HASAR, GEOTEKNİK RİSKLER VE DENETİM BAŞARISIZLIKLARI ÜZERİNE BİR VAKA ANALİZİ (1983-2025)

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ÖZET

Türkiye'de yapı güvenliği diskuru, haklı olarak sismik risklere odaklanmıştır. Ancak, sismik aktivite olmaksızın, "kendiliğinden" meydana gelen yapısal göçmeler, en az depremler kadar ciddi ve sistemik sorunlara işaret etmektedir. Bu bildiri, 1983 Diyarbakır Hicret Apartmanı faciasından 29 Ekim 2025 Gebze çöküşüne kadar olan süreçte, Türkiye'de kamuoyuna yansıyan başlıca deprem dışı progresif (bütüncül) göçme vakalarını kronolojik ve analitik bir yöntemle incelemektedir. Vaka kataloğu metodu kullanılarak, her bir olayın (Gebze 2025, Konya 2025, Kartal 2019, Konya 2004, Diyarbakır 1983/2007) bilirkişi raporları, arşiv kayıtları ve teknik analizler ışığında göçme patolojileri sınıflandırılmıştır. Analizler, bu göçmelerin "ani" veya "bilinmeyen" sebeplerden değil; (1) Tasarım, malzeme ve imalat aşamasındaki brüt mühendislik hataları, (2) Taşıyıcı sisteme sonradan yapılan bilinçsiz müdahaleler (kolon kesme, kaçak kat), (3) Geoteknik-Yapısal Etkileşim (Geometrik düzensizlik ve doğrudan zemin desteği kaybı) ve (4) Bu süreçlerin tamamındaki kritik denetim başarısızlıkları gibi birikimli ve progresif hasar mekanizmalarının sonucu olduğunu ortaya koymaktadır. Özellikle Gebze (2025) vakası, asimetrik plana sahip (kama formlu) bir yapının, doğrudan metro tünel aksı üzerindeki zemin boşalması (undermining) sonucu nasıl bir kinematik devrilme (toppling) mekanizmasıyla göçtüğünü göstermesi açısından literatürde özgün bir yere sahiptir. Bu çalışma, sismik riskin ötesinde, mevcut yapı stoğunun "statik" güvenliğine ve özellikle kentsel altyapı projelerindeki geoteknik risklerin denetimine yönelik acil politika ihtiyacını vurgulamayı amaçlamaktadır.

Anahtar Kelimeler: Progresif Göçme, Yapısal Güvenlik, Geoteknik-Yapı Etkileşimi, P-Delta Etkisi (P-\Delta), Denetim Başarısızlığı, Vaka Analizi.

1. GİRİŞ

Türkiye'nin bir deprem ülkesi olduğu gerçeği, yapı mühendisliği ve ulusal afet politikalarının merkezinde yer almaktadır. Odaklanma, büyük ölçüde sismik etkilere dayanıklı yapılar tasarlamak ve mevcut stoğu bu yönde güçlendirmek üzerine kuruludur. Ancak, bu odaklanma, yapıların "statik" yükler (kendi ağırlıkları ve kullanım yükleri) altındaki güvenliğini ve zamanla ortaya çıkan progresif hasar risklerini gölgede bırakma tehlikesi taşımaktadır.

Diyarbakır'da 1983'te 83 kişinin hayatını kaybettiği Hicret Apartmanı'ndan, Konya'da 2004'te 92 kişinin can verdiği Zümrüt Apartmanı'na ve İstanbul'da 2019'da 21 kişinin öldüğü Yeşilyurt Apartmanı'na kadar uzanan trajik bir liste, deprem olmaksızın da binaların "kendiliğinden" çökebildiğini acı bir şekilde kanıtlamıştır. Bu vakaların en günceli, bu bildirinin yazımından sadece bir gün önce (29 Ekim 2025) Gebze'de yaşanan ve analizlerimize göre bariz geoteknik ihmaller sonucu meydana gelen yapısal göçmedir.

Bu olaylar "ani" veya "bilinmeyen" sebeplerle değil; tasarım, imalat, kullanım ve denetim aşamalarındaki sistematik başarısızlıkların birikimli bir sonucu olarak gerçekleşmektedir. Bu bildiri, bu vakaları bir katalog altında toplayarak, bu "statik" göçmelerin ortak mühendislik patolojilerini analiz etmeyi ve gelecekteki benzer facialarını önlemek için dersler çıkarmayı hedeflemektedir.

2. YÖNTEM VE KAPSAM

Bu çalışmada, "Vaka Kataloğu Analizi" (Case Catalog Analysis) metodolojisi kullanılmıştır. Kapsam, 1983-2025 yılları arasında Türkiye'de meydana gelen, deprem dışı, progresif (bütüncül) ve can kaybına yol açan/potansiyeli yüksek olan apartman tipi yapılarla sınırlandırılmıştır. Metruk (terk edilmiş) yapıların veya kısmi çökmelerin çoğu analize dahil edilmemiştir.

Veriler, açık kaynaklı arşivlerden, (mevcutsa) TMMOB veya adli bilirkişi raporlarından, haber arşivlerinden ve Gebze (2025) vakası için sağlanan birincil kanıtlardan (Google Street View görüntüleri, CİMER yazışmaları, geoteknik analiz şemaları) derlenmiştir.

3. VAKA KATALOĞU VE PATOLOJİ SINIFLANDIRMASI

Türkiye'deki deprem dışı yapısal göçme envanteri incelendiğinde, göçme nedenlerinin zamanla 'brüt malzeme ve tasarım hatalarından', 'kentsel etkileşim ve insan müdahalesine' doğru evrildiği görülmektedir. 1983 Hicret Apartmanı ve 2004 Zümrüt Apartmanı vakaları, temel mühendislik hizmetlerinden yoksunluk ve düşük malzeme kalitesi (düşük beton dayanımı, yetersiz sargı donatısı) ile karakterize edilirken; 2019 Yeşilyurt ve 2025 Konya vakaları, mevcut taşıyıcı sisteme sonradan yapılan kontrolsüz müdahaleleri (kaçak kat, kolon kesilmesi) işaret etmektedir. Ancak 29 Ekim 2025 tarihli Gebze vakası, literatürde ayrışan bir patoloji sunmaktadır. Nispeten genç bir yapı stoğuna (13 yıl) dahil olmasına rağmen bina, malzeme yetersizliğinden ziyade, geoteknik-yapısal etkileşim (SSI) ihmali sonucu göçmüştür. BDışsal nizamda yürütülen metro kazısının yarattığı zemin gevşemesi ve farklı oturmalar, üst yapıda tolere edilemeyen $P-\Delta$ etkilerini tetiklemiş; bu durum yoğun kentleşme süreçlerinde ***'dışsal geoteknik risklerin'*** en az ***'içsel yapısal kusurlar'*** kadar kritik olduğunu ortaya koymuştur.

Analiz edilen temel vakalar ve göçme patolojileri Tablo 1'de özetlenmiştir.

Tablo 1: Türkiye'de Deprem Dışı Progresif Göçme Vakaları Kataloğu (1983-2025)

Vaka Konum	Tarih	Yapı Tipi / Yaşı	Vefat Sayısı	Göçme Patolojisi (Birincil Neden)
Gebze, Kocaeli	29.10.2025	7 Katlı Apt. (13 Yaşında)	4	Geoteknik-Yapısal Etkileşim: Dışsal kazı (Metro) kaynaklı zemin gevşemesi ve farklı oturma, $P-\backslash Delta$ etkisini tetikledi.
Konya, Selçuklu	24.01.2025	3-4 Katlı Apt. (31 Yaşında)	2	Taşıyıcı Sisteme Müdahale: Zemin katta yapılan tadilat sırasında kolon kesilmesi/zayıflatılması (Ana Şüphe).
Kartal, İstanbul (Yeşilyurt Apt.)	06.02.2019	8 Katlı Apt. (27 Yaşında)	21	Proje İhlali ve Malzeme Yetersizliği: 3 kaçak kat (aşırı yük), deniz kumu (korozyon) ve düşük beton mukavemeti.
Diyarbakır, Kayapınar (Alkan-1 Apt.)	04.02.2007	8 Katlı Apt. (14 Yaşında)	5 (Boşaltılmıştı)	Proje İhlali (Aşırı Yük): 4 kat ruhsatlı binanın 8 kat inşa edilmesi.
Konya, Selçuklu (Zümrüt Apt.)	02.02.2024	11 Katlı Apt. (7 Yaşında)	92	Brüt Tasarım ve İmalat Hatası: Hatalı zemin etüdü, yetersiz statik proje (P-Δ ihmali), düşük beton kalitesi ve yetersiz sargı donatısı.
Diyarbakır, Şehitlik (Hicret Apt.)	03.01.1983	7 Katlı Apt.	83	Brüt Malzeme ve İmalat Hatası: Ruhsatsız, projesiz yapı. "Kerpiç gibi" beton (düşük çimento) ve 6'lık donatı kullanımı.

4. MÜHENDİSLİK ANALİZİ VE TARTIŞMA

Katalogdaki vakalar "progresif göçme" ortak sonucunda birleşse de bu göçmeyi başlatan birincil mühendislik patolojileri farklılık göstermektedir. Bu patolojiler dört ana kategori altında incelenebilir:

4.1. Kategori 1: Brüt Tasarım, Malzeme ve İmalat Yetersizliği

Bu kategoride, yapı daha inşa edilirken "ölü doğmuştur" ve kendi statik ağırlığını dahi güvenle taşıyamamaktadır.

- **Vakalar:** Hicret Apt. (1983), Zümrüt Apt. (2004).
- **Mekanizma:** Hicret vakasındaki "kerpiç gibi" beton ve **Ø6**'lık donatı, yapının basit basınç gerilmesini **(P/A)** dahi karşılayamadığını göstermektedir. Zümrüt vakasında ise hatalı statik proje, düşük beton kalitesi ***(f_{ck})*** ve yetersiz etriye (sargılama) birleşerek, kolonların sünek (ductile) bir davranış gösteremeden, ani ve gevrek (brittle) bir şekilde kırılarak iflas etmesine yol açmıştır.



Şekil 1. *Diyarbakır Hicret Apt. 1983 ((Antoloji Diyarbakır, 2020))*



Şekil 2. *Konya Zümrüt Apt. 2004 (Anadolu Ajansı, 2020)*

4.2. Kategori 2: Proje İhlali ve Aşırı Yükleme (Kapasite Aşımı)

Bu kategoride, yapıya proje dışı yükler (genellikle kaçak katlar) eklenerek mevcut kapasitenin üzerine çıkılmıştır.

- **Vakalar:** Kartal-Yeşilyurt (2019), Diyarbakır-Alkan-1 (2007).
- **Mekanizma:** Kartal'da 5 katlık sisteme 3 kat daha eklenmesi, **P** (düşey yük) değerini projelendirilenden %60'a varan oranda artırmıştır. Bu aşırı yük, zamanla deniz kumunun neden olduğu korozyonla birleştiğinde, güvenlik katsayıları tamamen erimiş ve sistem iflas etmiştir.



Şekil 3. *İstanbul Kartal Yeşilyurt Apt 2019 (Evrensel, 2021)*

4.3. Kategori 3: Taşıyıcı Sisteme Sonradan Müdahale

Bu kategoride, başlangıçta stabil olan yapıya kullanım aşamasında yapılan bilinçsiz müdahaleler (kolon kesme) göçmeyi tetikler.

- **Vaka:** Konya-Selçuklu (2025).
- **Mekanizma:** Bir taşıyıcı kolonun kaldırılması, yük aktarım yolunu (load path) bozar ve yükün komşu elemanlara yeniden dağıtılmasına (load redistribution) neden olur. Bu ani aşırı yüklenme, komşu elemanlarda zincirleme bir iflasa (cascade failure) yol açar.



Şekil 4. *Konya Selçuklu 2025 (Ankara Masası, 2025)*

4.4. Kategori 4: Geoteknik-Yapısal Etkileşim (Deformasyon Kaynaklı İflas)

Bu, en karmaşık senaryodur ve bu bildirinin odağındaki Gebze vakası ile örneklendirilmiştir. Göçme, yapısal bir hatadan çok, dışsal bir geoteknik etkinin neden olduğu deformasyondan kaynaklanır.



Şekil 5. *Binanın enkazı kaldırıldıktan sonra ortaya çıkan görüntü*

- **Vaka:** Gebze (2025).
- **Mekanizma:** Bitişikteki metro kazısı, binanın bir tarafındaki zemini "gevşeterek" (Şekil 1), bir "Zayıf Zemin" alanı (image_3fc262.png) yaratmıştır. Bu, "farklı oturmaya" ve binada bir "devrilme" hareketine neden olmuştur. Bu devrilme hareketi, kolonlarda bir ilk deplasman ***(Δ)*** yaratmış ve ***P-\Delta*** (İkinci Mertebe) etkisini (image_4018fc.png) tetiklemiştir. $M^{II} = M^I + (P \times \Delta)$ formülündeki ikincil moment, kolonların ezilip-burkularak iflasına ve "pancake" çöküşe yol açmıştır.

5. EN KRİTİK ORTAK PAYDA: DÖRT AŞAMALI DENETİM BAŞARISIZLIĞI

Mühendislik patolojileri farklılaşsa da, bu altı vakanın tamamını birleştiren asıl kök neden, **sistematik denetim başarısızlığıdır**. Bu başarısızlık, bir binanın ömrünün dört kritik aşamasında da gözlemlenmiştir:

1. **Tasarım Denetimi Başarısızlığı:** Zümrüt Apt. (2004) vakasında olduğu gibi, hatalı zemin etütleri ve yetersiz statik projeler onaylanmıştır.

2. **İmalat Denetimi Başarısızlığı:** Hicret Apt. (1983) ve Kartal Apt. (2019) vakalarında olduğu gibi, sahada "kerpiç gibi beton" veya "deniz kumu" kullanılmasına rağmen binalar onay almıştır.

3. **Kullanım Aşaması Denetimi Başarısızlığı:** Kartal (2019) ve Konya-Selçuklu (2025) vakalarında olduğu gibi, binalara sonradan kaçak kat çıkılmasına veya kolon kesilmesine rağmen etkin bir denetim yapılmamıştır.

4. **Tehdit-Müdahale Denetimi Başarısızlığı:** Bu, Gebze (2025) vakasıyla ortaya çıkan en trajik kategoridir. Diğer üç denetim aşaması başarılı olsa bile, dışsal bir tehdit (metro kazısı) ortaya çıktığında ve bu tehdit T-8 ay önce (çatlaklar) ve T-2.5 ay önce (CİMER başvurusu)

resmi olarak bildirilmesine rağmen, denetim mekanizması "0.6mm sorun yok" diyerek fatal bir hata yapmış ve göçmeye davetiye çıkarmıştır.

6. SONUÇ VE ÖNERİLER

Bu vaka kataloğu, Türkiye'deki deprem dışı yapısal göçmelerin "münferit facialar" veya "kader" olmadığını; tasarım, uygulama, kullanım ve denetim disiplinlerinin tamamını kapsayan, derin ve sistemik sorunların öngörülebilir sonuçları olduğunu kanıtlamaktadır.

Bu bulgular ışığında aşağıdaki acil öneriler sunulmaktadır:

1. **Geoteknik Risk Alanı Tanımlaması:** Kentsel alandaki tüm derin kazı ve altyapı projeleri (metro, otopark vb.) için yasal olarak "geoteknik etki alanı" tanımlanmalı; bu alandaki komşu binaların sürekli monitörizasyonu (İnSAR, inklinometre, jeodezik ölçüm) zorunlu hale getirilmelidir.

2. **Tehdit-Müdahale Protokolü:** "Gebze İhmali"nin tekrarlanmaması için, yapısal risk (çatlak, oturma) şikayetlerine yönelik acil durum protokolleri oluşturulmalıdır. "0.6mm" gibi tehlikeyi minimize eden raporlar, daha derin bir incelemeyi (Tepkisel Eylem) tetiklemeli, süreci kapatmamalıdır.

3. **Mevcut Stok "Statik Güvenlik" Denetimi:** Mevcut yapı stoğunun denetimi sadece sismik risklere değil, "statik risklere" (malzeme bozulması-korozyon, kaçak kat, sonradan müdahale) karşı da genişletilmelidir.

4. **Adli Mühendislik Veri Tabanı:** Bu bildirideki gibi vakaların teknik bilirkişi raporları, ders alınması amacıyla kamusal ve akademik bir "Ulusal Yapısal Göçme Veri Tabanı"nda anonimleştirilerek paylaşılmalıdır.

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DETERMINATION OF LIME-BASED MORTAR ELASTIC MODULUS AFTER ELEVATED TEMPERATURE

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ABSTRACT

Historical masonry structures undergo progressive deterioration over time, necessitating restoration and structural strengthening interventions. Due to their chemical and mechanical compatibility with original historical materials, hydraulic lime-based mortars (HLMs) are widely employed in conservation practices. This study investigates the elastic modulus performance of hydraulic lime-based mortar with ultrasonic pulse velocity test after elevated temperature. Mortar prisms composed of HLMs were prepared in accordance with relevant material testing standards. The specimens were exposed to elevated temperatures ranging from 200 °C to 800 °C and subsequently subjected to ultrasonic pulse velocity tests. A total of 19 specimens were prepared for the elevated temperature tests (ETTs), consisting of three test specimens, one temperature-monitoring specimen for each temperature level, and three reference specimens. The reference specimens were tested under ambient laboratory conditions, whereas the remaining specimens, after exposure to elevated temperatures, were allowed to cool naturally to room temperature prior to testing. All specimens were subsequently evaluated under identical testing conditions to ensure the consistency and comparability of the experimental results. Based on the experimental results and subsequent evaluations, it was determined that the hydraulic lime-based mortars (HLMs) experienced a gradual decline in their elastic modulus with increasing temperature. This study provides valuable insights into the thermal performance of masonry walls constructed with hydraulic lime-based mortars (HLMs), thereby contributing to the advancement of fire-resistant materials for the restoration and preservation of historical structures.

Keywords: Lime-based mortar, Mechanical Properties, Elevated Temperarue Test, Elastic Modulus, Ultrasonic Pulse Velocity (UPV)

1. INTRODUCTION

The purpose of this study is to assess the influence of elevated temperatures on the elastic modulus of hydraulic lime-based mortars (HLMs) by employing ultrasonic pulse velocity testing. By examining the mechanical behavior of HLM specimens exposed to temperatures ranging from 200 °C to 800 °C, the study aims to determine the extent of degradation in their elastic properties. This investigation ultimately seeks to provide a deeper understanding of the thermal performance of HLMs used in historical masonry structures, contributing to the development of more effective and fire-resistant restoration materials and conservation strategies.

Kara et al. (2025) investigated mechanical properties of lime based mortar, bricks and masonry prism at elevated temeprature. The study investigates the mechanical behaviour of masonry walls built with hyraulic lime based mortars and clay bricks after elevated temperature that used to evalute historical masonry elements. The authors prepared several types and numbers of the specimen which was cured standard conditions and subsequently exposed temepratures from 200 °C to 800 °C. After heating, the specimens were performed flexural and compression tests. Digital image correlation was performed and compared to actual displacement measurements on masonry prism. Reults show that progressive loss of mechanical properties, elastic modulus of masonry prisms while temperature increases. The authors also evaluated thermal properties of materials after elevated temperatures and validated with finite element analysis versus testing. This study offers critical numerical and emprical data for post-fire structural assessment of historical masonry structures. **[Kara et al., 2025]**.

The paper by Pachta et al. (2018) investigates the physical and mechanical performance of lime-based mortars under elevated temperatures, with a view toward the behavior of historic or repair mortars when exposed to elevated temperatures. Several types of mortar were prepared and exposed to elevated temperatures from 200 °C up to 1000 °C. After the elevated temperature exposure, weight loss, volüme change, porosity, dynamic modulus of elasticity and flexural, micro structural changes and compression stregth were evaluated. The study concludes that lime mortars exhibit high thermal resistant compared to cement-based mortars. These findings provide a useful benchmark for evaluating mortar performance under thermal stress, which could complement non-destructive testing methods such as UPV when assessing post-fire residual strength or structural integrity in masonry elements. **[Pachta et al., 2018]**.

El Dandachy, M. E. Et al. (2024) investigated the mechanical and durability properties of metakaolin-based geopolymer mortars compared to conventional OPC mortars after elevated temperatures affects. Specimens were heated from 100 °C up to 900 °C, and their compressive strength, mass loss, ultrasonic pulse velocity (UPV), and gas permeability were measured. The geopolymer mix showed notably higher thermal resistance than ordinary portlant cement mortar, maintaining structural integrity and even improving in performance at moderate temperatures. The results show that geopolymer mortars experience a significant increase in compressive strength at around 200 °C, becasue of additional geopolymerization and matrix densification induced by temperature. After this peak, strength gradually decreases at higher temperatures. Ultrasonic pulse velocity test followed a similar trend: a slight decrease at low temperatures, a peak at 200 °C, and a progressive reduction with further heating, reflecting stiffness loss and microcracking. Overall, the study highlights the strong high temperature behavior of metakaolin-based geopolymers and demonstrates the usefulness of Ultrasonic pulse velocity test as a nondestructive tool for evaluating their residual mechanical performance. **[El Dandachy et al., 2018]**.

EN 1996-1-2 covers fire resistant design rules for masonry structures and decribes how material properties, including those of masonry mortar, change under elevated temperatures. The standard gives not only design rules for mortar but also fire resistance of masonry elements both structural and non-structural elements. Mortar is the critical part of the masonry strcutures that is adressed temperature dependent matrial properties such as compressive strength, stiffness and deformation characteristics. The reduction factors reflects the propgressive loss of mortar bonding, increased porosity and loss of cohesion at elevated temperatures. The standard also covers that fire performance of masonry with combined behaviour of units and mortar and emphasizes that mortar type such as general purpose, thin layer, and light wieght mortar affect thermal stability and load bearing capacity. In summary, the code treats mortar as a critical component governing masonry fire resistance, with its temperature-dependent mechanical degradation directly influencing the structural reliability of masonry members during fire exposure. However, the standard inludes for mortar strentgh class M5 and M10. Because of the fact that, in this study, relatively high strength lime based mortar M15 class were examined. **[EN 1996-1-2, 2024]**.

This study aims to emphasize the elastic modulus measured with Ultrasonic Pulse Velocity non destructive test at ambient and elevated temperature and their relevance to modern restoration practices and seismic strengthening of heritage buildings.

2. MATERIALS AND METHODS

In this research, a comprehensive evaluation of the fire resistance performance of high-lime mortars (HLMs), UPV tests were conducted. For this purpose, the mortars and masonry prism specimens were produced in accordance with the relevant material testing standards, and the prisms were assembled using the prepared mortar mixes. Following specimen preparation, all units were exposed to elevated temperatures ranging from 200 °C to 800 °C, after which they were subjected to mechanical testing in bending and compression to assess the influence of thermal loading on their structural behaviour. **[Kara et al., 2025]**.

A total of fifty specimens were incorporated into the high-temperature testing program. However, Ultrasonic pulse velocity (UPV) measurements were performed exclusively on the mortar specimens and were evaluated as part of this study. For each temperature level, three specimens were assigned for experimental mechanical testing, one specimen was fitted with thermocouples for monitoring internal temperature evolution, and three additional specimens served as reference samples. Within the scope of the elevated-temperature tests (ETTs), 20 specimens were prepared for the masonry prisms, 15 for the clay bricks, and 15 for the masonry mortars. The technical properties of the selected mortar are presented in Table 2.1, and the hardened mortar exhibited an average density of approximately 1850 kg/m³. **[Kara et al., 2025]**. In this study only the 15 mortar specimens were evaluated for UPV tests and results were reported for elastic modoulus.

Table 2.1. Technical data of Teknorep 520 EX**.**

General Information	
Material Structure	Special blend with natural hydraulic lime base and adjusted gradients
Cement Content (%)	0%
Appearance	Off-white and white coffee
Shelf Life	12 months in dry place in unopened packaging.
Package	20 kg kraft bag
Application Information	
Implementation Process	Min. 30 min at 20 °C
Application Ground Temperature	(+5 °C)–(+35 °C)
Grain Size	0–8 mm
Application Thickness	Each storey 1–5 cm
Performance Information	
Flexural Strength	4.0 N/mm^2
Compressive Strength (EN 1015-11)	15–20 N/mm^2 (M15 Class)
Modulus of Elasticity	7000 N/mm^2
Water Vapor Permeability (EN 1745)	$\mu < 35$
Capillary Water Absorption (EN 1015-18)	0.2 $kg\ m^{-2}\ h^{-0.5}$
Bond Strength	>0.15 N/mm^2
Reaction to Fire	A1

For each temperature level applied to the masonry prisms, three specimens were allocated for mechanical testing, one specimen was dedicated exclusively to thermal monitoring, and three additional specimens were used as reference samples. The reference group was tested under ambient laboratory conditions without exposure to elevated temperatures. All remaining specimens were allowed to cool naturally to room temperature following the high-temperature phase and were subsequently tested under the same ambient conditions as the reference samples to ensure a consistent basis for comparison. The specimens assigned for temperature monitoring were not subjected to mechanical testing; instead, they were equipped with embedded thermocouples to record the internal temperature development throughout the heating process **[Kara et al., 2025]**.

The mortar specimens were prepared by mixing Teknorep 520 EX in the laboratory using a water-to-mortar ratio of 20/3.1–3.3, in accordance with the manufacturer's recommendations. The fresh mixture was then placed into prismatic molds measuring 40 mm × 40 mm × 160 mm, following the procedures outlined in EN 1015-11 **[EN 1015-11, 2019].** Immediately after

casting, the specimens were enclosed in polyethylene bags to ensure a controlled curing environment with a relative humidity of 95% ± 5%, as prescribed by the standard (Figure 2.1).



Figure 2.1: Masonry mortar preparation as per EN 1015-11 **[EN 1015-11, 2019], [Kara et al., 2025]**.

The mechanical testing program presented by Kara et al. (2025) was conducted at the Construction Materials, Fire, and Acoustic Laboratory of the Turkish Standards Institution (TSE) in Istanbul, Turkey. During the experiments, the specimens were subjected to constant temperature levels of 200 °C, 400 °C, 600 °C, and 800 °C, in accordance with the temperature–time curve specified in the ISO 834-1 standard fire protocol **[ISO 834-1:2014]**. These high-temperature conditions were provided by a specialized furnace equipped with natural gas burners, engineered to ensure stable and uniform heating throughout the duration of the tests **[Kara et al., 2025].**

In compliance with the provisions of EN 1363-1 **[EN 1363-1:2020]**, the specimens were positioned 750 mm away from the furnace burner zone to avoid direct flame impingement and to ensure that heating occurred predominantly through convection and radiation, as required in standardized fire resistance testing. Furnace temperatures were controlled and measured using two-plate K-type thermocouples placed approximately 100 mm away from the surfaces of the specimen, following the specifications of EN 1363-1 **[EN 1363-1:2020].**

The tests were conducted in an indicative furnace with internal dimensions of 1.5 m × 1.5 m × 1.5 m. Two natural gas burners, each providing 600 kW of power, were utilized to achieve the prescribed heating curve. As direct flame impingement is prohibited under fire resistance standards, the burners were positioned at the front and back of the furnace to prevent direct exposure of the specimens to the flame. The configuration of the indicative furnace is illustrated in Figure 2.2. and specimens were given in Figure 2.3.

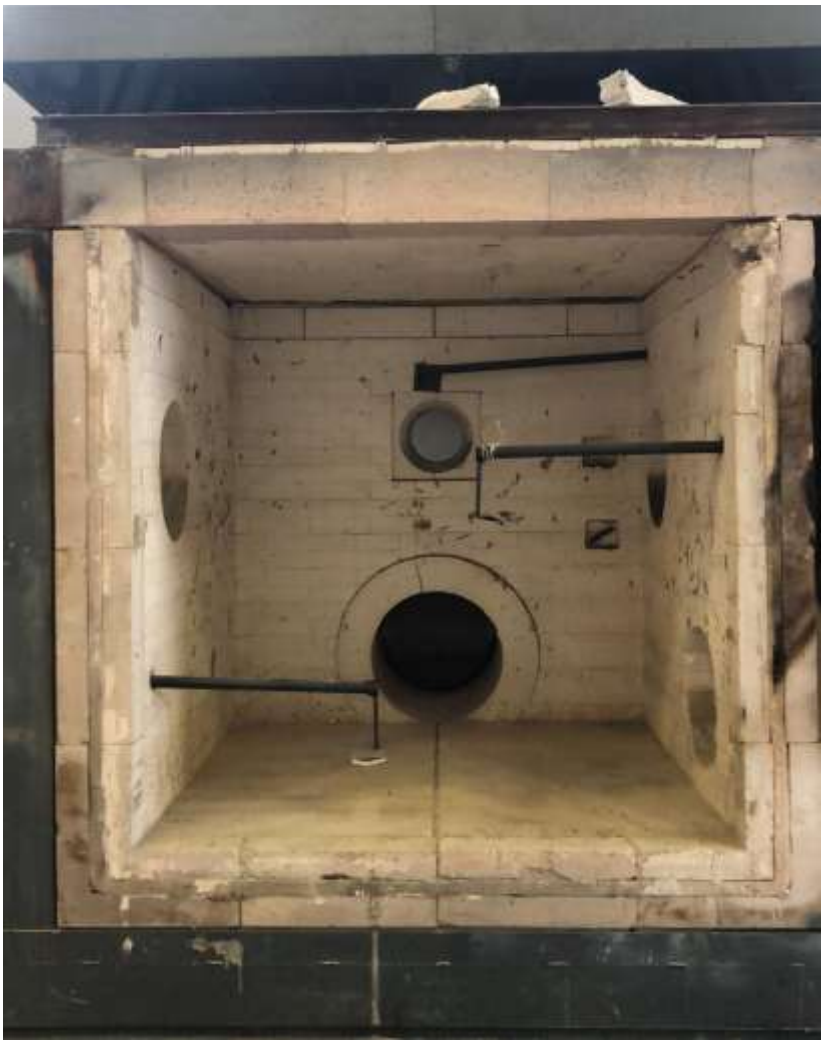

Figure 2.2: Indicative furnace for fire resistance tests.

To precisely monitor the internal temperature evolution within the test material, an additional K-type Inconel thermocouple was embedded in a designated control specimen (Figures 2.3). This instrumented specimen was not included in the mechanical testing program; instead, it functioned solely as a monitoring unit, enabling the accurate recording of the thermal profile experienced by the material during high-temperature exposure.

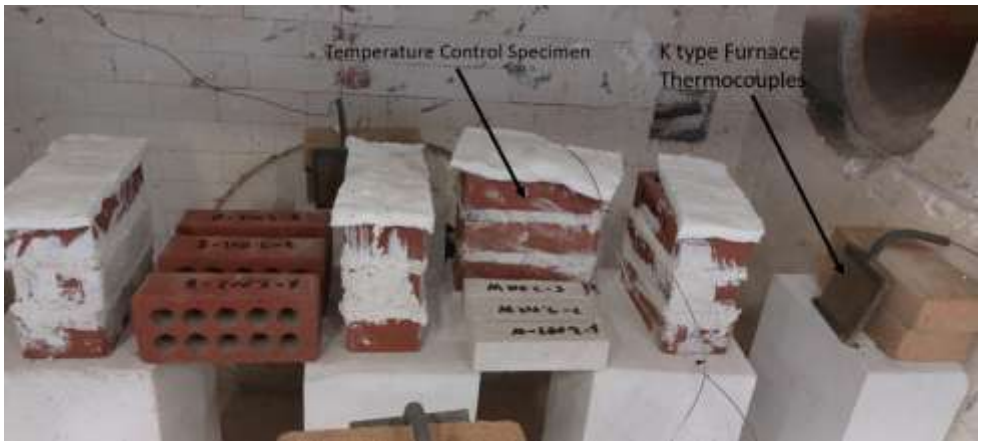

Figure 2.3. Elevated temperature test placement in the furnace **[Kara et al., 2025]**.

The recorded heating regimes of the furnace are given below and compared with ISO 834-1 temperature-time curve in Figure 2.4:

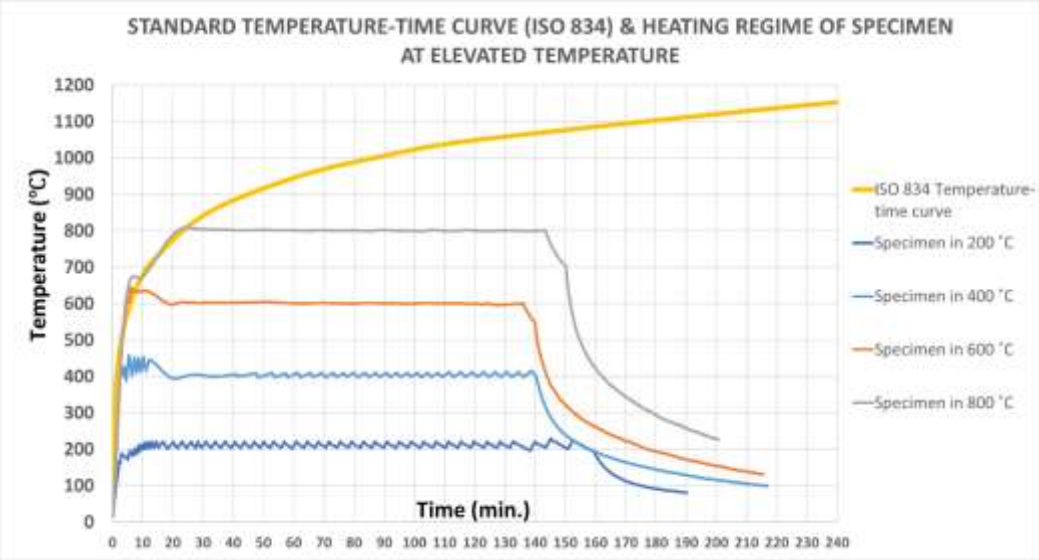

Figure 2.4. Elevated temperature test of the actual heating regime. **[Kara et al., 2025]**.

The procedure for determining the compressive strength of masonry mortar was carried out in accordance with EN 1015-11 **[EN 1015-11, 2019].** For each ambient and elevated temperature condition, three specimens were tested, and the average compressive and flexural strength values were calculated. A Zwick hydraulic testing machine with a 100 kN capacity was employed to measure the compressive strength of mortar specimens sized 40 × 40 × 160 mm, following the requirements of EN 1015-11 **[EN 1015-11, 2019].** After flexural strength testing had been completed on the three specimens, compressive tests were conducted on the resulting six fractured halves, in line with the standards described in EN 1015-11 **[EN 1015-11, 2019]**, and the mean values were subsequently determined. All testing procedures were performed on M15 lime-based mortar (Figure 2.5.). **[Kara et al., 2025].**



Figure 2.5: Masonry compression and flexural test (before and after the test). **[Kara et al., 2025]**.

Elastic modulus of masonry walls exposed to fire decline as the compressive and flexural strength losses. The elastic modulus of masonry mortar specimen was determined in accordance with TS EN 12504-4 by measuring the P-wave and S-wave velocities using the Ultrasonic Pulse Velocity (UPV) method. **[TS EN 12504-4, 2021]**

Mortar and prism specimens prepared for use in masonry construction were exposed to fire at temperatures of 20°C, 200°C, 400°C, and 600°C, subsequently UPV method was performed. A Pundit PL200 device was employed for UPV measurements, and 54 kHz P-wave and 40 kHz S-wave transducers were used to determine the respective wave velocities.

Before use, the transducers were regularly calibrated using calibration rods. This calibration procedure was repeated prior to each new specimen measurement to eliminate potential errors arising from calibration drift as illustrated in Figure 2.6.



Figure 2.6. Calibration of UPV device

During the measurements, the transducers were positioned to ensure direct transmission through the specimens. This arrangement ensured that the wave path extended from the centre of one transducer to the centre of the other, enabling precise pulse-velocity determination and providing optimal alignment with maximum signal amplitude. When measuring P-wave velocity, any gaps between the specimen surface and the transducers were filled using ultrasonic gel. For each measurement mode, a minimum of six readings was taken, and the average values were recorded. The measurements figures are given in Figure 2.6 and Figure 2.7.

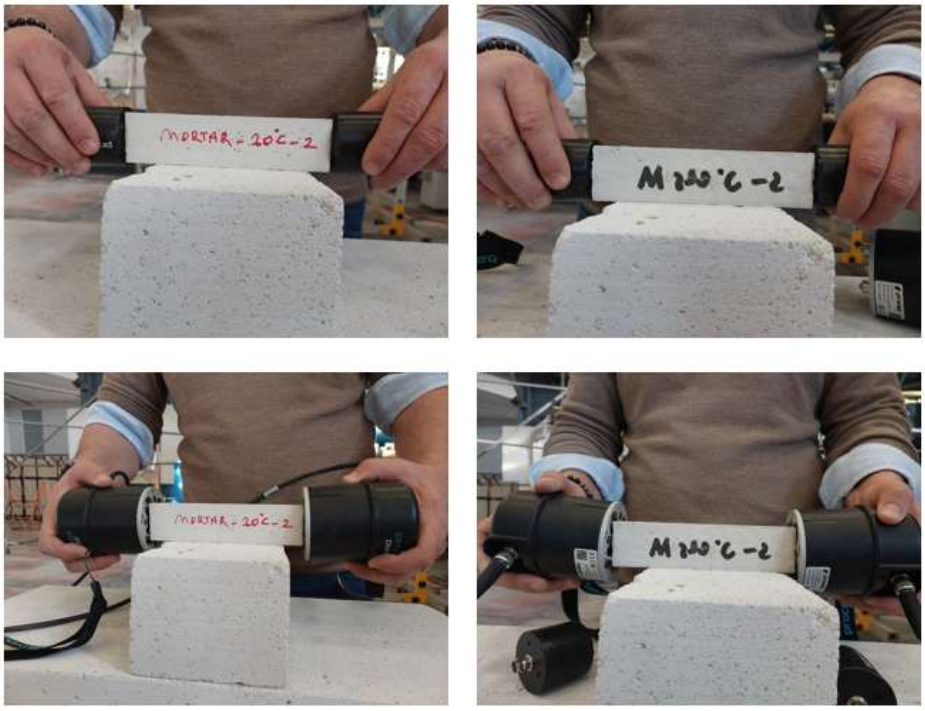

Figure 2.6. UPV measurements for 20 °C and 200 °C

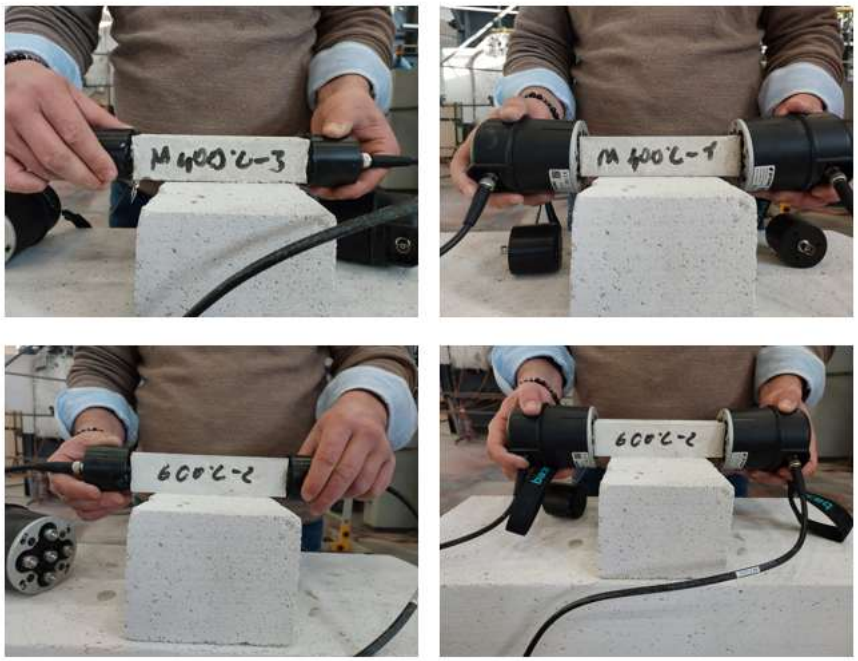

Figure 2.7. UPV measurements for 400 °C and 600 °C

3. RESULTS AND DISCUSSION

By establishing a correlation between P-wave velocity and the experimentally obtained compressive and flexural strengths, a predictive equation was developed. This equation, presented as an outcome of the study, enables researchers to estimate post-fire compressive strength based solely on wave velocity measurements, thereby eliminating the need for

destructive testing methods. The results are given in Figure 3.1, Figure 3.2, Figure 3.3, Figure 3.4 and Table 3.1.

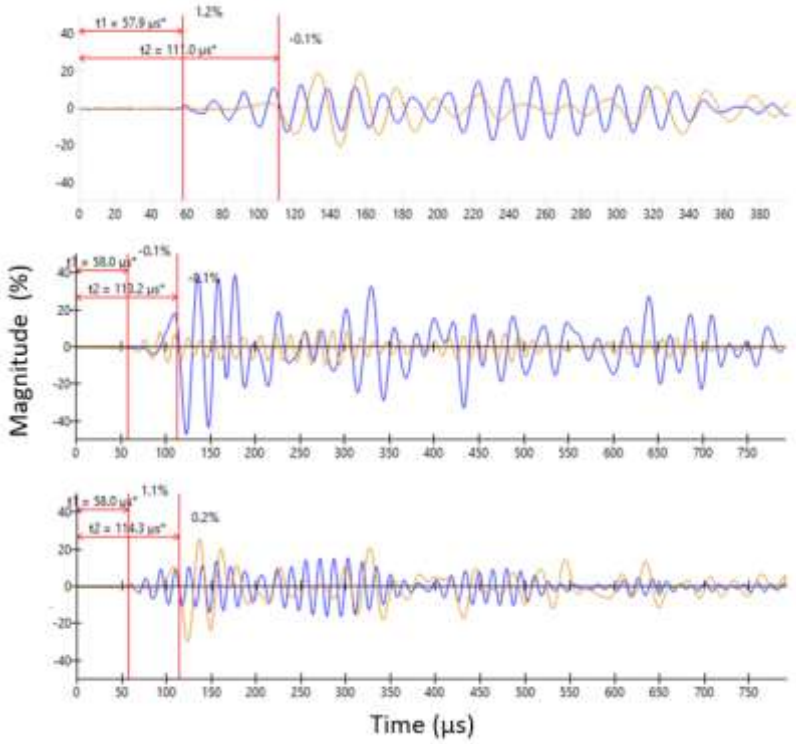

Figure 3.1. UPV measurements results for 20 °C

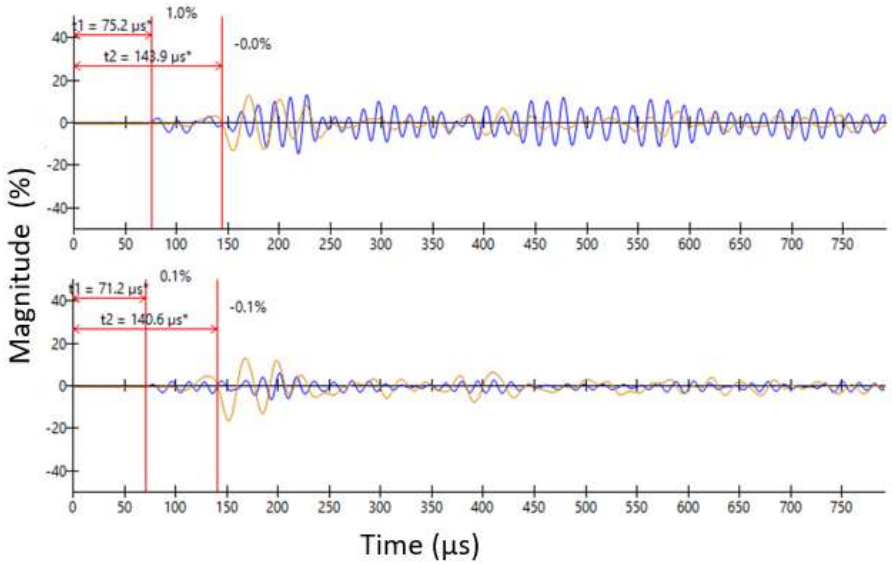

Figure 3.2. UPV measurements results for 200 °C

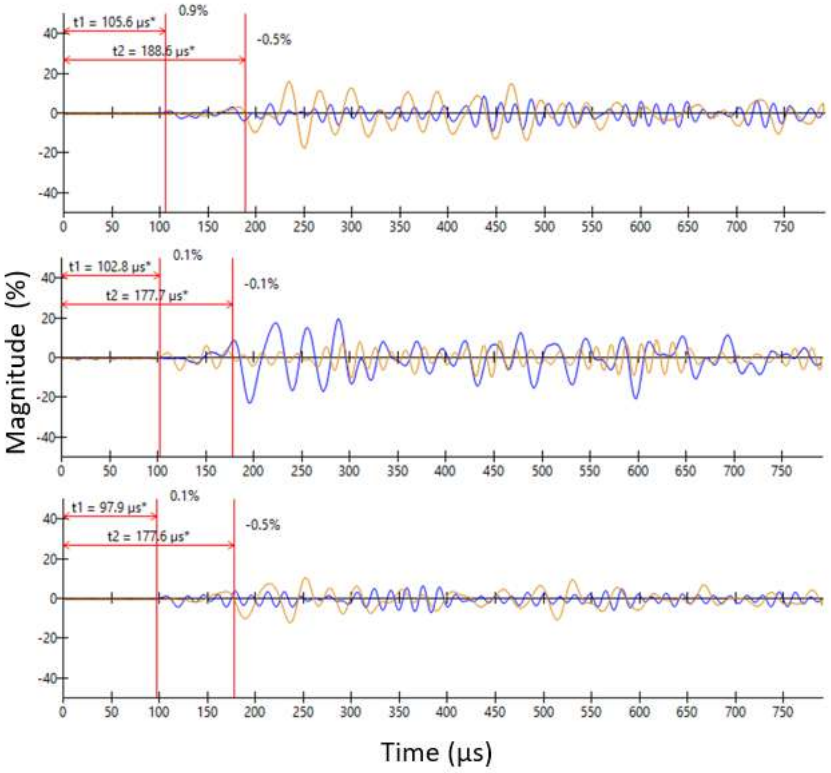

Figure 3.3. UPV measurements results for 400 °C

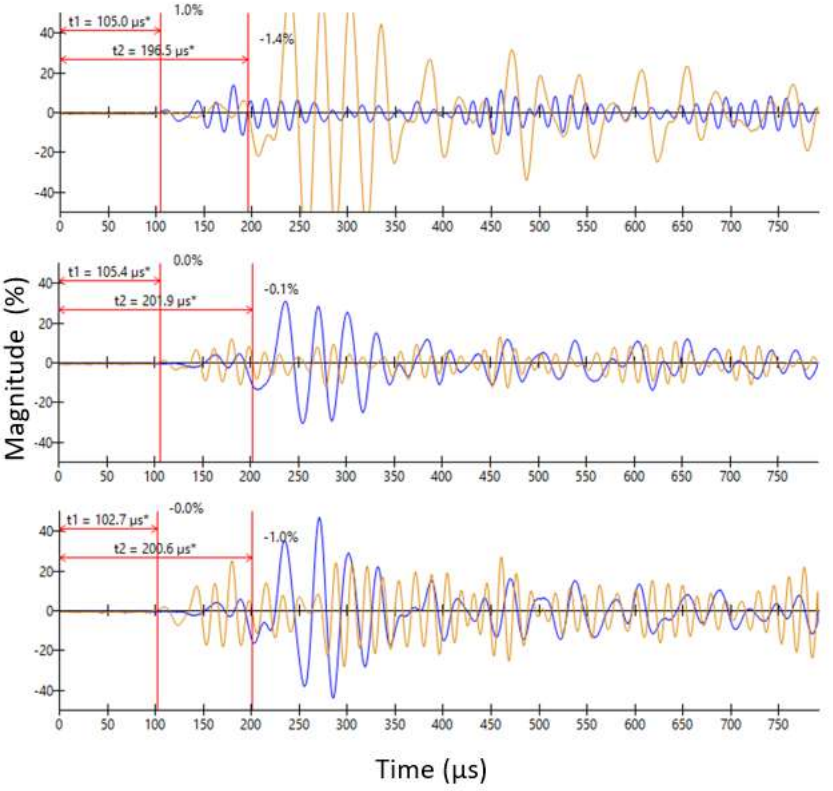

Figure 3.4. UPV measurements results for 600 °C

Table 3.1. UPV test results on M15 Lime-based Mortar

Mortar Specimen	Transmission Time (µs)		Pulse Velocity (m/s)		Elastic Modulus (Mpa)
	Average	Stable State	Average	Stable State	
20 °C-1	57.42	58	2771,66	2778	8470
20 °C-2	62.56	58	2682,20	2754	8270
20 °C-3	62.16	58	2609,78	2759	8410
200 °C-1	75.28	75	2125	2133	5210
200 °C-2	72	72	2215	2219	5500
200 °C-3	71.6	72	2224,20	2225	-
400 °C-1	105.85	107	1468,45	1490	2970
400 °C-2	101.5	103	1535,42	1571	3150
400 °C-3	99.17	101,5	1571,83	1570	3110
600 °C-1	99.26	99	1610,25	1617	2750
600 °C-2	108.35	107	1195,20	1515	2830
600 °C-3	105.66	105	1496,50	1525	2730

The 800 °C test specimen were totally cracked after temperature exposure, so, results are not shown in the table. In addition, measurement was taken for brick units and masonry prism units, however satisfactory results cannot be taken due gaps inside the specimen, so only masonry mortar results were reported. In the results, it is shown that elastic modulus of ambient temperature is very close to declared value by manufacturer. It is gradually decrease for elevated temperature.

4. CONCLUSION

The UPV test results indicate that hydraulic lime-based mortars (HLMs) exhibit a gradual decline in mechanical performance as temperature increases. At 20°C, the specimens exhibited the highest pulse velocities (approximately 2700–2800 m/s) and elastic modulus values (approximately 8300–8500 MPa). The application of heat at a temperature of 200°C resulted in a significant reduction in UPV, which is indicative of the initiation of microcracking. By 400 °C, pulse velocity decreased to approximately 1500 m/s, signifying substantial structural degradation, which became even more pronounced at 600 °C. The findings demonstrate a strong inverse relationship between temperature and ultrasonic pulse velocity (UPV), indicating that ultrasonic pulse velocity is a reliable indicator of thermal damage and stiffness degradation in HLMs, thereby underscoring their susceptibility to high-temperature exposure.

Acknowledgments

This paper represents a component of the corresponding author's doctoral thesis, and the author is grateful to all those who contributed to its completion.

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COMPARATIVE ANALYSIS OF MODERN SATELLITE-DERIVED GRAVITY MODELS WITH THE EGM2008 REFERENCE MODEL

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ABSTRACT

This study evaluates the performance of three recent satellite-based static global gravity models—WHU-SPWU-GOGR2022S, GOSG02S, and Tongji-GMMG2021S—by comparing them with the reference model EGM2008, given the importance of an accurate gravity field representation for geodetic and geophysical applications such as geoid determination, crustal structure interpretation, and mass transport analysis. Gravity disturbance (δg) values were computed for all models at maximum spherical harmonic degrees 10, 50, 100, 200, and 300 on a global grid and for a regional test area covering Türkiye. As expected, the level of spatial detail increases with harmonic degree, and at n = 300 all models resolve high-resolution features of the gravity field. Globally, the three satellite-based models show strong agreement with EGM2008; differences in minimum and maximum δg values at n = 300 remain small and are not geophysically significant, while WHU-SPWU-GOGR2022S and GOSG02S yield almost identical results at several degrees, reflecting the consistency of GOCE-only solutions. Over Türkiye, all models produce similar gravity disturbance values, roughly between −133 and +60 mGal, and reproduce comparable spatial patterns. Difference maps reveal local discrepancies of up to about ±10 mGal, mainly over marine areas and parts of eastern Türkiye, while standard deviations remain around 5.7–5.8 mGal; the smallest value is obtained for the EGM2008–Tongji-GMMG2021S comparison, indicating that this combined GOCE+GRACE model matches EGM2008 most closely. Overall, the results demonstrate that recent satellite-based global gravity models are highly consistent with EGM2008 and suitable for regional geodetic and geophysical studies over Türkiye, while future work may validate them against independent terrestrial gravity or GNSS/leveling data to further quantify regional model accuracy.

Keywords: Global Gravity Models, Gravity Disturbance, EGM2008

1. INTRODUCTION

Current satellite-based gravity models are products based on modern geodetic measurement techniques that enable the determination of the Earth's gravity field with high accuracy and resolution. Satellite design, orbital characteristics, observation techniques, and measurement and evaluation methods play a decisive role in the development of these models (Üstün, 2008). Precise modeling of the gravity field is made possible, particularly by low-Earth-orbit (LEO) satellites, through positioning, accelerometer recordings, satellite-to-satellite tracking, and gradiometry measurements. In this context, missions such as the Gravity Recovery and Climate Experiment (GRACE), GRACE Follow-On (GRACE-FO), Challenging Minisatellite Payload (CHAMP), and Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) are among the leading satellite missions that have developed new approaches to determining the global gravity field (Akdoğan et al., 2019). Measurements obtained from these LEO missions are not only useful in modeling the gravity field; It is critical for a wide range of geodetic and hydrological applications, including monitoring the terrestrial water cycle, determining groundwater changes, analyzing oceanographic processes, monitoring ice mass loss, and drought assessments. The Earth Gravitational Model 2008 (EGM2008), created by combining these satellite measurements with classical ground measurements and altimetry data, is one of the most comprehensive models currently available that provides a high-definition global representation of the Earth's gravity field. Produced by integrating satellite gravity, surface gravity measurements, and sea surface topography data, EGM2008 successfully represents even small-scale gravity anomalies thanks to its high degree of accuracy (n = 2190) (Öztürk, 2015). Therefore, it is widely used as a reference model in various geodetic applications.

Gravity disturbance is a physical quantity that represents deviations or anomalies in the gravity field. It is mostly caused by density differences in the subsurface, crustal structure, and topographic effects. Gravity disturbances provide important information in areas such as mineral exploration, geological structure identification, crust-mantle boundary modeling, and understanding dynamic Earth processes.

This study aims to compare gravity disturbance data derived from three different satellite-based gravity models with the EGM2008 model. In this context, the global gravity field of each model will be expanded to 10th, 50th, 100th, 200th, and 300th degrees, and detailed according to harmonic resolution. Subsequently, the differences between these satellite models and EGM2008 will be calculated, and comparative evaluations will be conducted. These analyses will contribute to demonstrating the accuracy, resolution capabilities, and modeling performance of satellite-based gravity models. As a result, the study aims to contribute to the evaluation of satellite-based gravity models in terms of accuracy and resolution and to present important results for more detailed modeling of the gravity field.

2. STUDY AREA, DATA AND METHOD

2.1. Study Area

The primary study area was defined as the global scale. A preliminary assessment was conducted by testing the results of the gravity models to be compared in the same geographic regions on Earth.

The secondary study area is Türkiye, covering the region between 36°–42° North latitude and 26°–45° East longitude. The three recent satellite-based static gravity field models published by ICGEM: WHU-SPWU-GOGR2022S, GOSG02S, and Tongji-GMMG2021S, were analyzed and evaluated in conjunction with the EGM2008 model. Gravity disturbance values

corresponding to different spherical harmonic orders were calculated and compared with values derived from EGM2008, which served as control data.

2.2. Data

Global gravity (geopotential) models (GGMs) are sets of spherical harmonic coefficients representing the Earth's gravity field at different wavelengths of the spectrum. These coefficients are derived from satellite orbital disturbances, satellite gravity gradiometers, satellite altimeters, and/or ground gravity measurements. In this context, GGMs are generally classified into three main groups (Featherstone, 2002). The first group consists of geopotential models derived solely from satellite gravity data. The second group includes combined models produced by combining satellite gravity data with satellite altimetry measurements and/or terrestrial gravity observations. The third group consists of models obtained by improving satellite-based or combined GGMs at a regional scale using local gravity data for a specific region (Avşar et al., 2015). Detailed information on global geopotential models, including their spherical harmonic coefficients and standard deviations, can be obtained from the International Center for Global Earth Models (ICGEM) website (Tepeköylü and Üstün, 2007).

Detailed information on the models used in the study is presented in Table 1.

Table 1. GGMs selected for testing, (S: satellite data, G: terrestrial gravity, A: altimeter)

GGMs	Year	n_{max}	Data	Source
WHU-SPWU-GOGR2022S	2023	300	S(GOCE), S(GRACE)	Zhao et al. (2023)
GOSG02S	2023	300	S(GOCE)	Xu et al. (2023)
Tongji-GMMG2021S	2022	300	S(GOCE), S(GRACE)	Chen et al. (2022)
EGM2008	2008	2190	A,G, S(GRACE)	Pavlis et al. (2012)

2.2.1. WHU-SWPU-GOGR2022S

WHU-SWPU-GOGR2022S is a high-resolution GGM developed by Southwest Petroleum University (SWPU) and Wuhan University (WHU). The model is a static spherical harmonic solution, complete to degree 300, constructed by combining the static normal equations from the GOCE and GRACE missions. The combined use of high-order satellite data provides a detailed and accurate representation of the Earth's gravity field (Zhao et al., 2023).

2.2.2. GOSG02S

The GOSG02S model is a static geopotential model based solely on gravity gradiometer and orbital tracking data from the GOCE satellite. This model has been completed up to the 300th spherical harmonic degree and provides a high-resolution representation of Earth’s gravity field (Xinyu et al., 2023). It reflects the strengths of the GOCE mission, particularly in its high-order gravity information content.

2.2.3. Tongji-GMMG2021S

Tongji-GMMG2021S is a combined global geopotential model developed by Tongji University, combining the static normal equations of the GOCE and GRACE missions. The model represents the Earth's gravitational field with high accuracy, with a spherical harmonic solution complete to the 300th degree (Chen J. et al., 2022). Thanks to the low-order contribution of the GRACE data and the high-order contribution of the GOCE data, the model demonstrates strong performance at both long and short wavelengths.

2.2.4. EGM2008

EGM2008 (Earth Gravitational Model 2008) is a high-order global geopotential model developed by the U.S. National Spatial-Intelligence Agency (NGA). The model is constructed

by combining the normal equations derived from the GRACE-based ITG-GRACE03S global gravity field model with terrestrial gravity measurements, sea surface topography, and satellite altimeter data using the least-squares method. This model, with a spherical harmonic expansion completed to 5 degrees and corresponding to an angular resolution of approximately 5 minutes, reaches a horizontal resolution of approximately 9 × 9 km in the equatorial region. EGM2008 provides a highly accurate gravity field representation by integrating the comprehensive 5′ × 5′ resolution global gravity anomaly database with gravity information from GRACE (Zeray Öztürk, 2015). In terms of orbit determination performance, EGM2008 has an accuracy level comparable to other GRACE-based geopotential models. Compared to EGM96, EGM2008 provides an approximately sixfold improvement in resolution and a three- to sixfold improvement in accuracy, depending on location and gravity magnitude (Pavlis et al., 2012). EGM2008 is a comprehensive and highly accurate gravity model widely used in geophysical, geodetic, oceanographic, and engineering applications.

2.3. Method

In this study, gravity disturbance data derived from current satellite-based GGMs were used. For each GGM, gravity disturbances were calculated separately for maximum spherical harmonic orders of 10, 50, 100, 200, and 300. The models used in the analysis were WHU-SWPU-GOGR2022S, GOSG02S, and Tongji-GMMG2021S, obtained from the website of the International Center for Global Earth Models (ICGEM). EGM2008 was selected as the reference model for comparison. Gravity disturbance values obtained for different maximum orders were both numerically calculated and visualized as maps, thus demonstrating how gravity disturbances change with order, and a comparative evaluation of the models was performed against EGM2008.

2.3.1. Gravity Disturbance and Gravity Anomaly

Geodetic and geophysical gravity measurements are performed on the physical surface of the Earth and within its true gravity field. Traditionally, the latitude, longitude and orthometric height of a gravity station are determined; however, with the advent of satellite-based positioning technologies such as GNSS/GPS, the ellipsoidal heights of these points can also be obtained with high accuracy. This advancement provides a more precise connection between the physical surface, the ellipsoid and the geoid.

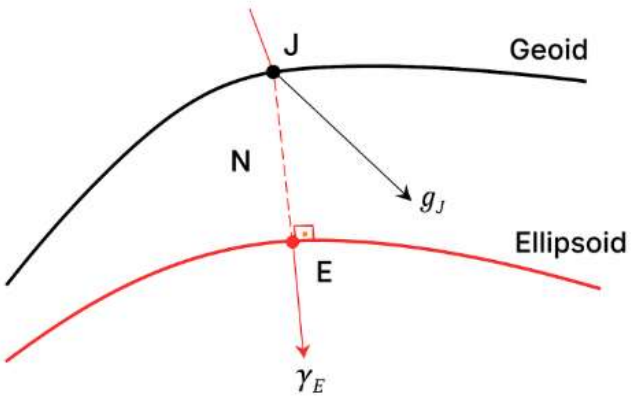

Figure 1. Vectors related to gravity anomaly and disturbance

The difference between the real gravity vector at a point **J** on the geoid, g_J, and the normal gravity vector γ_E at the point **E** where the ellipsoid normal through J intersects the ellipsoid, is called the **gravity anomaly**:

$$\Delta g = g_J - \gamma_E \tag{1}$$

Gravity anomalies constitute the fundamental input for determining geoid heights through Stokes-type integral formulations in physical geodesy. If the normal gravity is evaluated not at the point E on the ellipsoid surface but at the observation point J itself, the resulting quantity is the gravity disturbance:

$$\delta g = g_j - \gamma_J \tag{2}$$

Gravity disturbance is conceptually simpler than the gravity anomaly and is gaining importance in modern geodetic applications due to the availability of accurate GNSS-derived ellipsoidal heights. For this reason, many contemporary gravity field studies increasingly favor gravity disturbance instead of the classical gravity anomaly.

Gravity disturbance at a point P can be computed using GGMs expressed in spherical harmonics (Hoffmann-Wellenhof & Moritz, 2006):

$$\delta g = \frac{GM}{R}\sum_{n=2}^{\infty}\left(\frac{R}{r}\right)^{n+1}\frac{(n+1)}{r}\sum_{m=0}^{n}\bar{P}_{nm}(\cos\theta)[\Delta\bar{C}_{nm}\cos m\lambda + \Delta\bar{S}_{nm}\sin m\lambda] \tag{3}$$

In the formula, θ denotes the polar angle, λ the longitude, and r the geocentric radius of the point. GM is the Earth's gravitational parameter and R is the Earth's mean radius. The symbols n and m represent the degree and order of the spherical harmonic expansion, respectively. The term $\bar{P}_{nm}$ denotes the fully normalized associated Legendre functions, while $\Delta\bar{C}_{nm}$ and $\Delta\bar{S}_{nm}$ are the fully normalized spherical harmonic coefficients representing the Earth's gravity field.

3. RESULTS

3.1. Gravity Disturbance (δg) Derived from GGMs at Different Degrees

The GGMs used in this study were first evaluated globally at several maximum spherical harmonic degrees. The computed gravity disturbance values at degrees 10, 50, 100, 200, and 300 were visualized to assess their spatial characteristics. The minimum and maximum values produced by each model up to degree 300 were calculated (Table 2). As expected, increasing the maximum degree of the spherical harmonic expansion resulted in a higher level of detail in all models. For n_{max} = 10, the WHU-SWPU-GOGR2022S and GOSG02S models yielded identical minimum and maximum values, whereas Tongji-GMMG2021S differed from EGM2008 by approximately 0.1 mGal. However, these deviations were sufficiently small to be considered negligible. For n_{max} = 50, the models again showed very similar behavior, and no meaningful discrepancies were observed in terms of their gravity disturbance values. At n_{max} = 100, both the minimum and maximum values increased for all models as a natural consequence of the finer spatial detail introduced by the higher-degree expansion. At n_{max} = 200, the models still exhibited no significant differences in their global extrema. Likewise, for n_{max} = 300, no clear distinction was observed between the models at the global scale. Although the global comparisons indicate broadly consistent performance among the models, more detailed regional analyses may be conducted to further evaluate and contrast their accuracy and reliability, particularly in areas of complex gravity field structure.

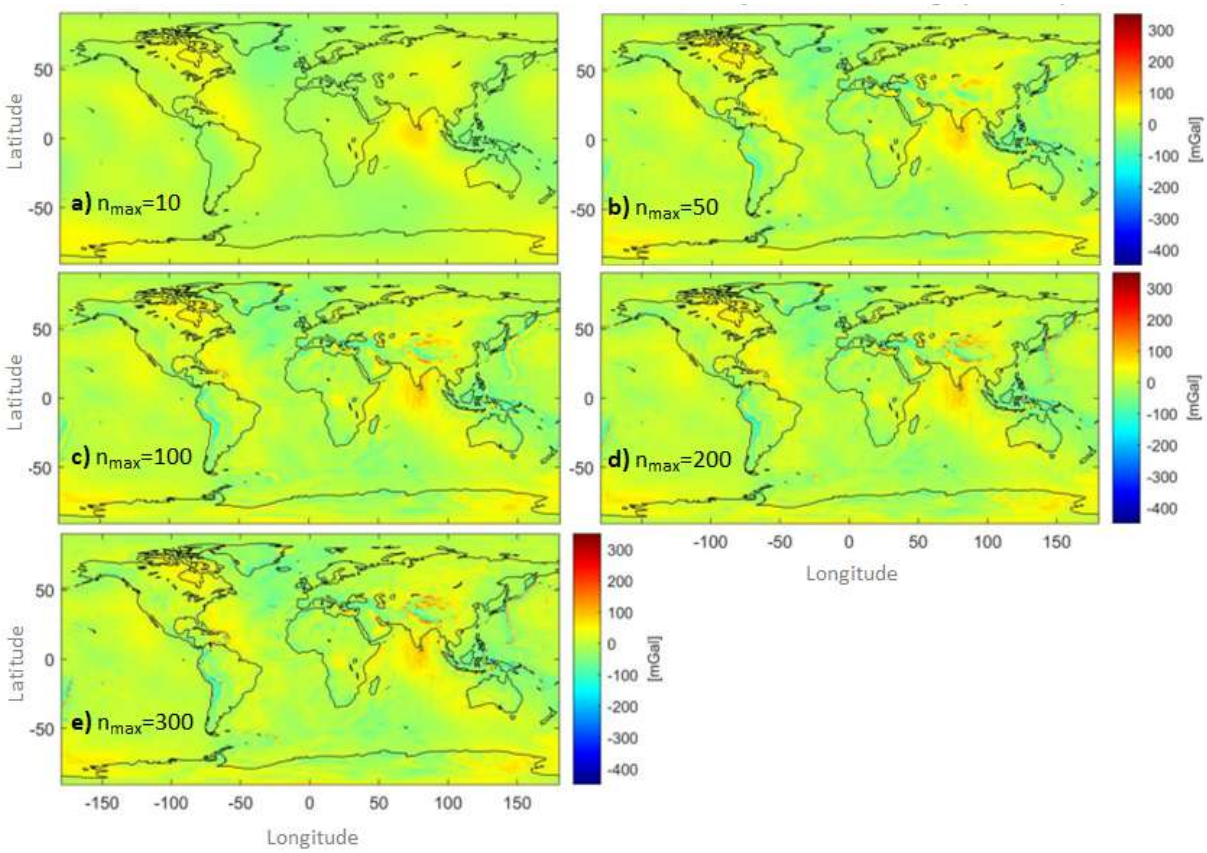

Figure 2. Gravity disturbances calculated at different degrees (n=10, 50, 100, 200, 300) for the EGM2008 model

Gravity disturbance maps computed from EGM2008 for different spherical harmonic degrees are presented in Figure 2. Although the full EGM2008 model is published up to degree 2190, in this study it is truncated at degree 300 to enable a consistent comparison with the other gravity models. As the maximum degree of expansion increases, the gravity field representation becomes progressively more detailed, revealing smaller-scale gravity disturbances. Higher spherical harmonic degrees thus allow for a more refined and spatially detailed characterization of Earth's gravity field.

Gravity disturbance maps computed for the GOSG02S model at different spherical harmonic degrees are presented in Figure 3. The GOSG02S model, derived exclusively from GOCE satellite observations, was released with a maximum spherical harmonic expansion of degree 300. In this study, the model was evaluated up to its published maximum degree in order to enable a consistent comparison with the other GGMs.

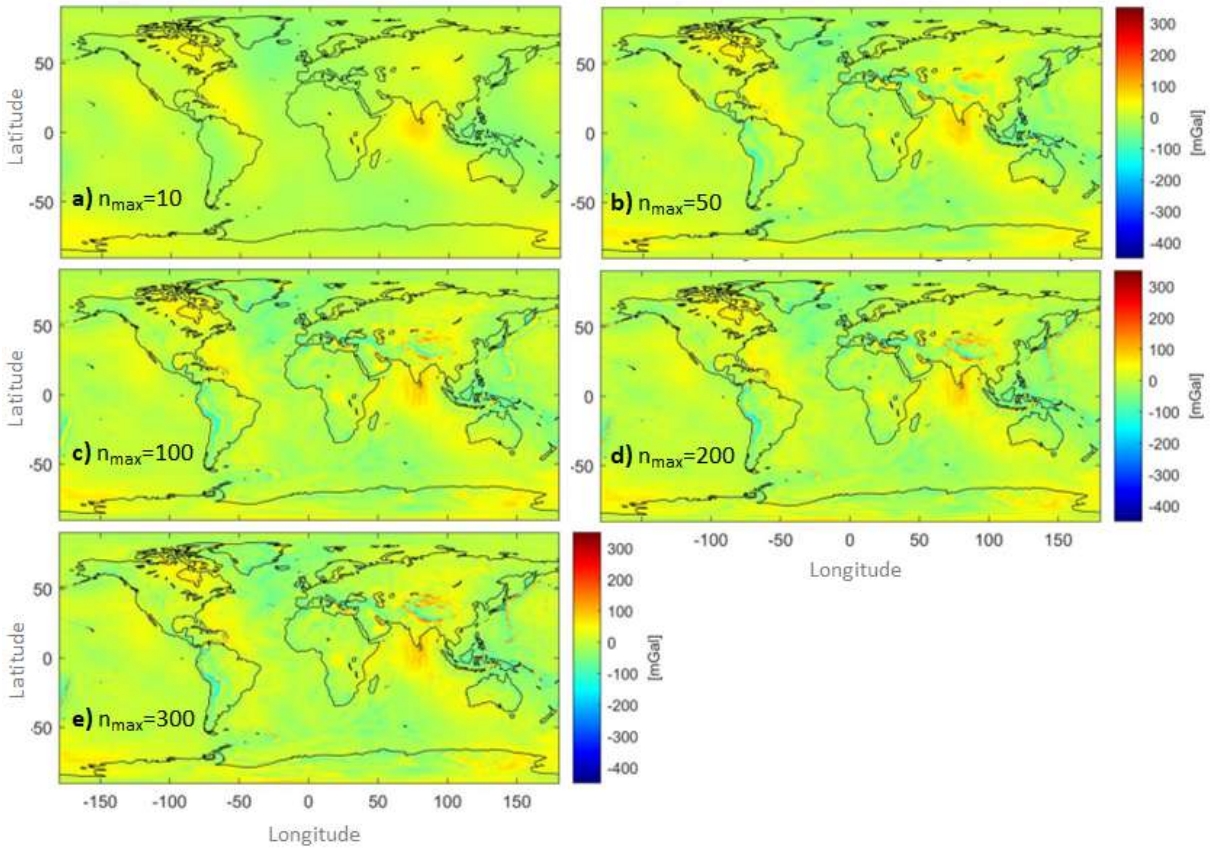

Figure 3. Gravity disturbances calculated at different degrees (n=10, 50, 100, 200, 300) for the GOSG02S model

The gravity disturbance maps computed for Tongji-GMMG2021S at various maximum spherical harmonic degrees are presented in Figure 4. The Tongji-GMMG2021S model, derived from combined GOCE and GRACE satellite data, was originally published with a maximum spherical harmonic expansion of degree 300. In this study, the model was likewise evaluated up to degree 300 to enable a consistent comparison with the other GGMs.

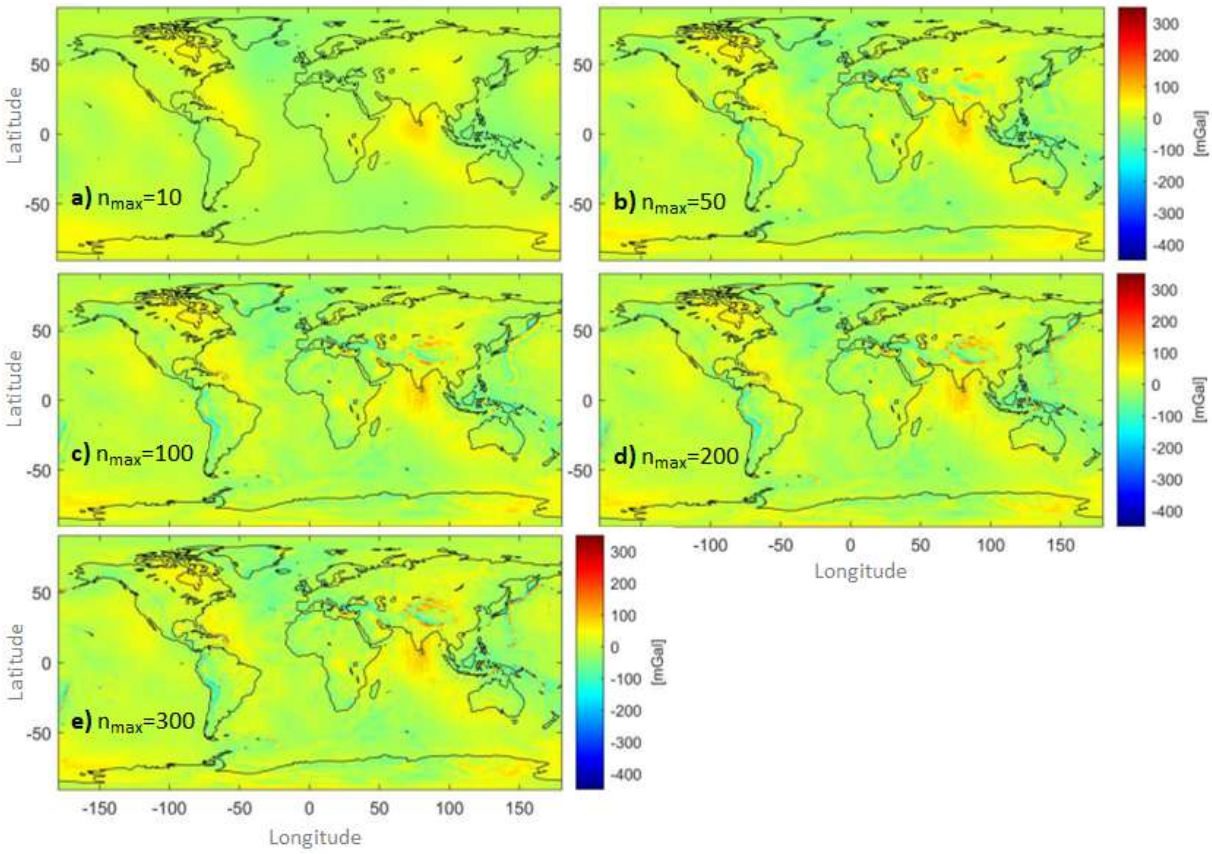

Figure 4. Gravity disturbances calculated at different degrees (n=10, 50, 100, 200, 300) for the Tongji-GMMG2021S model

Gravity disturbance maps derived from the WHU-SPWU-GOGR2022S model at various spherical harmonic degrees are presented in Figure 5. The WHU-SPWU-GOGR2022S model is a combined gravity field solution constructed from GOCE and GRACE satellite data. The model is published with a maximum spherical harmonic expansion of degree 300, and in this study, it is likewise evaluated up to degree 300 to ensure consistency and comparability with the other gravity models.

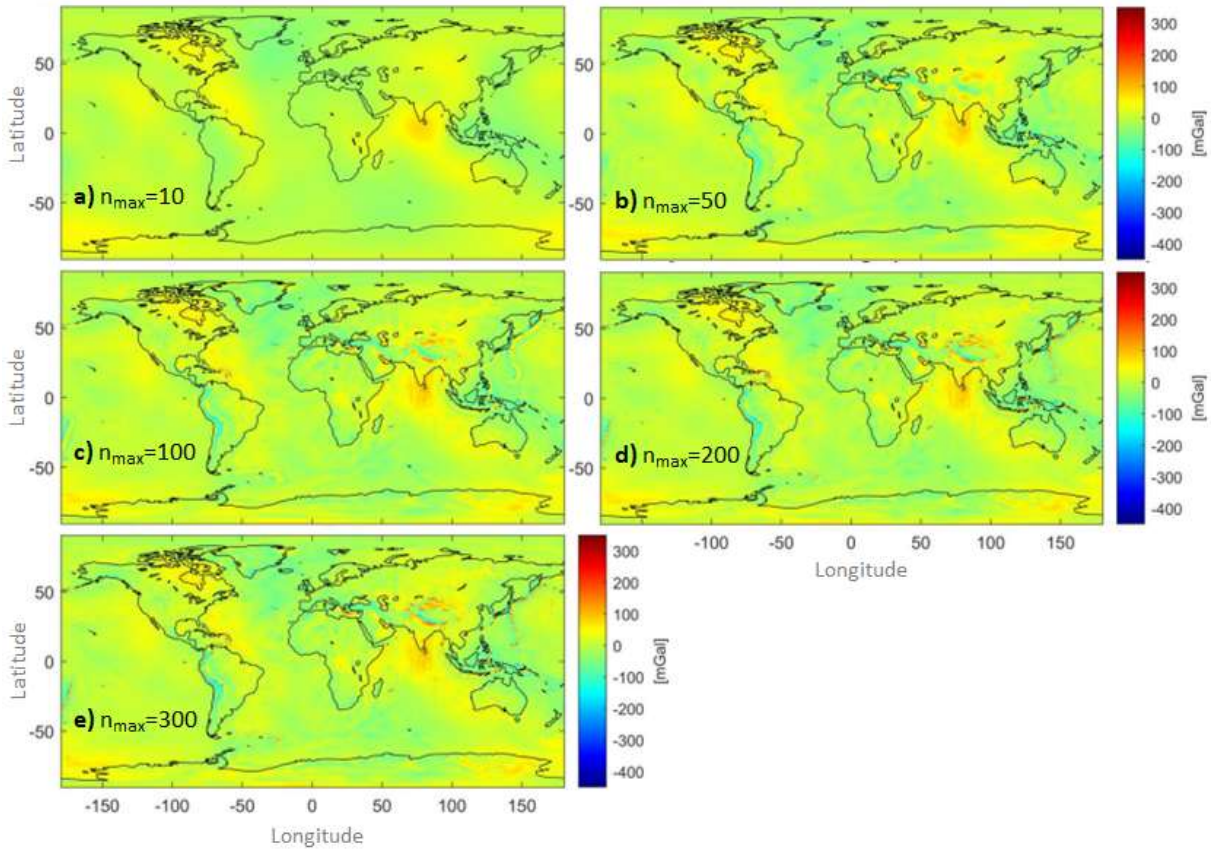

Figure 5. Gravity disturbances calculated at different degrees (n=10, 50, 100, 200, 300) for the WHU-SPWU-GOGR2022S model

Table 2. Gravity disturbance values of models at different degrees [mGal]

Model	n_{max}=10		n_{max}=50		n_{max}=100		n_{max}=200		n_{max}=300	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
EGM2008	-51.94	77.48	-109.49	96.07	-168.90	175.99	-332.92	316.91	-496.68	324.57
WHU-SWPU-GOGR2022S	-51.93	77.48	-109.49	96.06	-168.07	179.02	-336.12	315.39	-442.36	323.48
GOSG02S	-51.93	77.48	-109.50	96.06	-168.05	179.04	-336.12	315.38	-442.27	323.49
Tongji-GMMG2021S	-51.92	77.47	-109.50	96.06	-168.10	179.04	-336.05	316.06	-445.88	325.37

3.2. Results in Türkiye

Regional analysis of the GGMs was conducted for the area covering Türkiye, bounded by latitudes 36°–42° N and longitudes 26°–45° E. The models were computed up to degree 300. Figure 6 shows the gravity disturbance values for 4 GGMs in Türkiye at n_{max}=300. The minimum, maximum, and mean gravity disturbance values obtained from these computations are presented in Table 3. According to the results in Table 3, the models produced similar outcomes and remain closely aligned with the reference model, EGM2008. The results also

indicate that gravity disturbance values close to 0 mGal occur in the Southeastern Anatolia Region, particularly between latitudes 35°–39° N and longitudes 38°–39° E.

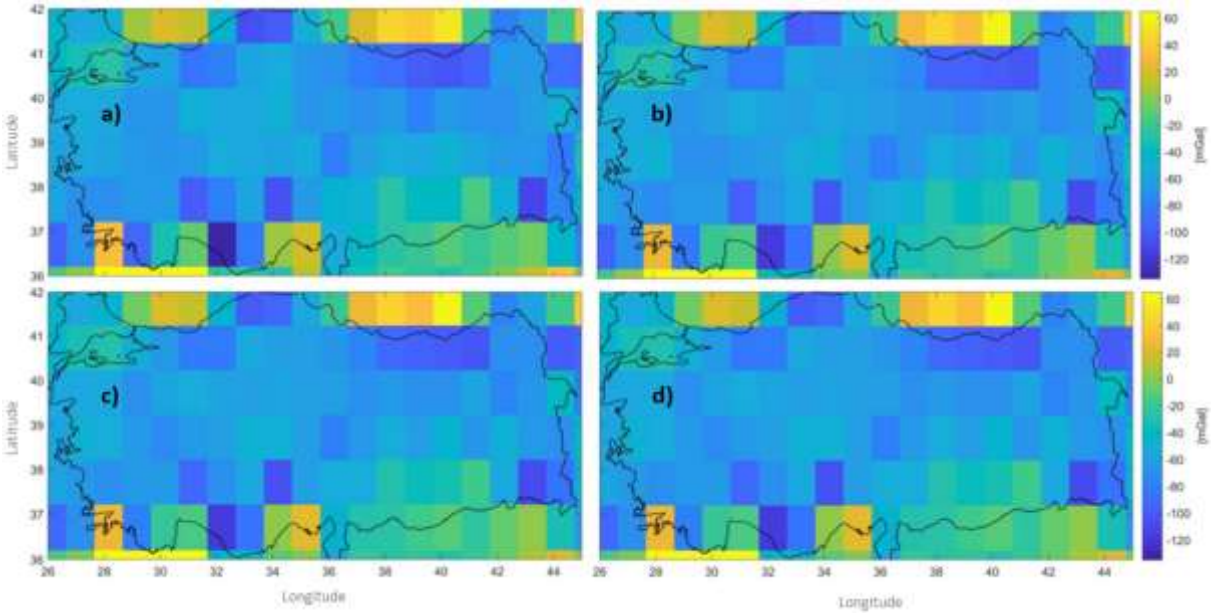

Figure 6. Gravity disturbance values of models for n_{max}=300 in Türkiye [mGal]
(**a)**EGM2008, **b)**Tongji-GMMG2021S, **c)**GOSG02S, **d)**WHU-SPWU-GOGR2022S)

Table 3. Min max and average values of the models for n_{max}=300 [mGal]

Model	n_{max}=300		
	Min	Max	Mean
EGM2008	-133.502	53.963	-51.649
WHU-SWPU-GOGR2022S	-118.690	59.134	-51.118
GOSG02S	-118.672	59.120	-51.129
Tongji-GMMG2021S	-118.865	60.482	-51.159

3.3. Gravity Disturbance Differences (Δδg) Derived from GGMs

Differences between EGM2008, selected as the reference model for n_{max} = 300, and the WHU-SWPU-GOGR2022S, GOSG02S, and Tongji-GMMG2021S models were calculated, and the results are presented in Figures 7, 8, and 9, as well as Table 4.3. Differences of the order of ±10 mGal were observed in the Black Sea, Aegean, and Mediterranean regions, as well as in some parts of the Eastern Anatolia Region. When the minimum, maximum, mean, and standard deviation values were evaluated, it was determined that the lowest standard deviation value was obtained from the differences between EGM2008 and the Tongji-GMMG2021S model (Figure 8).

The standard deviation differences between the models reached a maximum of 0.2 mGal. This very low difference demonstrates that the models exhibit a high level of consistency and produce similar results. In particular, a small difference such as 0.2 mGal supports the

reliability of the relevant gravity models and shows that it does not create a significant difference in application areas.

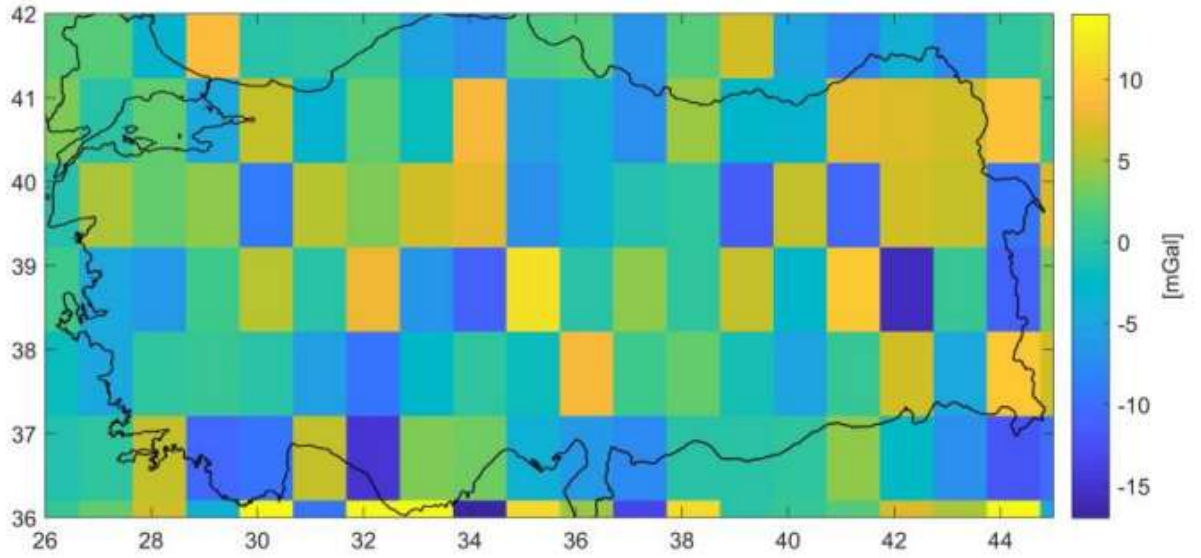

Figure 7. EGM2008 – GOSG02S (n_{max}=300)

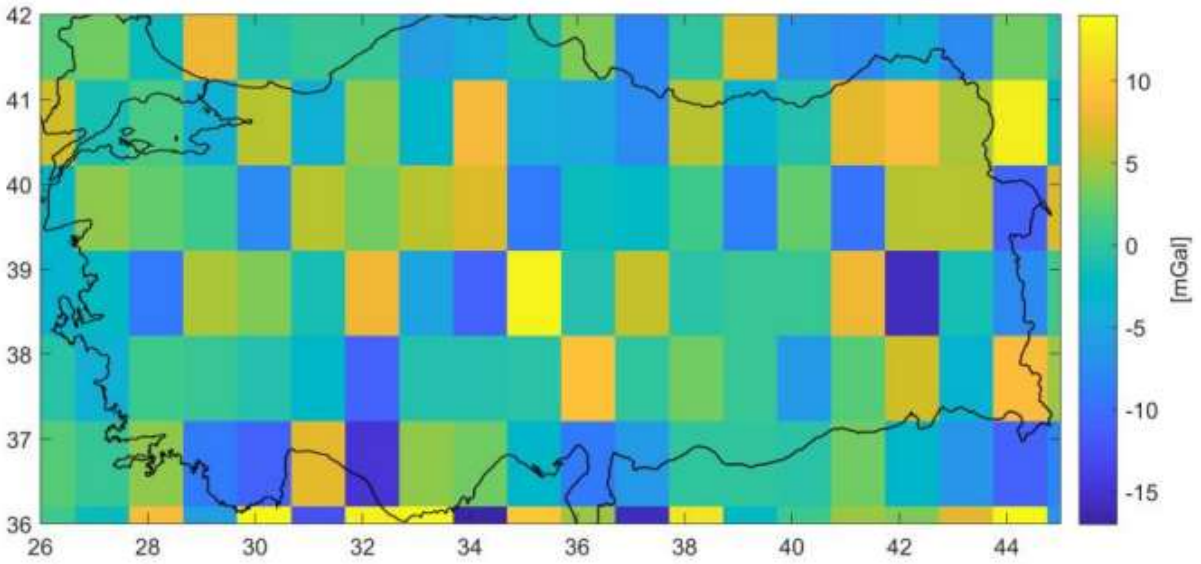

Figure 8. EGM2008 – Tongji-GMMG2021S (n_{max}=300)

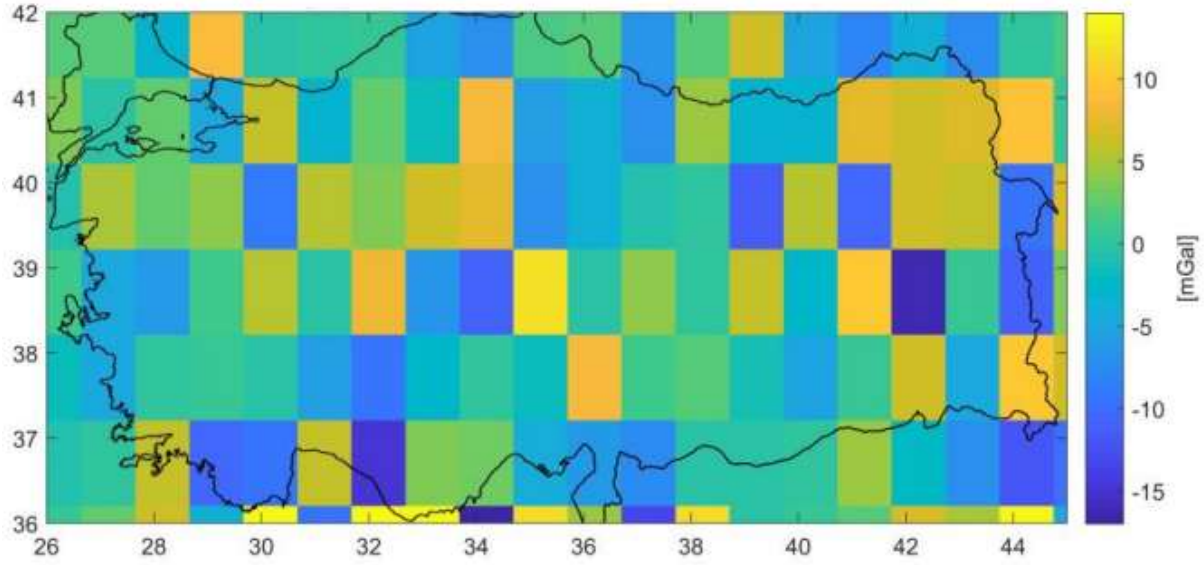

Figure 9. EGM2008 – WHU-SWPU-GOGR2022S (n_{max}=300)

Table 4. Statistical results of the differences of GGMs for n_{max}=300 [mGal]

Model	Min	Max	Mean	Std
EGM08-GOSG02S	-16.020	11.975	-0.520	5.813
EGM08-TongjiGMMG2021S	-15.723	13.336	-0.490	5.685
EGM08-WHUSWPU-GOGR2022S	-16.048	11.963	-0.053	5.812

4. CONCLUSION

To assess the accuracy of GGMs and to identify the most suitable model, gravity disturbances obtained from satellite-based GGMs at various maximum degrees were compared, and statistical indicators were computed. The global-scale analysis demonstrated that the models exhibit highly consistent behavior. For the region of Türkiye, the gravity disturbance differences between the models and EGM2008 were examined. Among these comparisons, the lowest standard deviation was observed for the difference between EGM2008 and Tongji-GMMG2021S. Since the discrepancies did not exceed 0.2 mGal, it can be stated that the models have comparable levels of accuracy. Nevertheless, when considering the standard deviation values of the differences, the Tongji-GMMG2021S model constructed by combining GOCE and GRACE satellite data emerges as the preferable option. In conclusion, although the Tongji-GMMG2021S model demonstrated superior performance at higher degrees, the GOSG02S and WHU-SWPU-GOGR2022S models also produced consistent results at specific degrees. For future improvements, the performance of these models can be further evaluated by conducting comparisons with additional regional datasets across Türkiye, enabling a more comprehensive accuracy assessment.

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PV PANEL YÜZEYİNDE OLUŞAN KİRLENMENİN PANEL PERFORMANSINA ETKİSİNİN DENEYSEL OLARAK İNCELENMESİ

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ÖZET

Enerji toplumların büyümesiyle ihtiyacın da giderek arttığı önemli bir kaynaktır. Enerji, fosil kaynaklardan sağlanabildiği gibi yenilenebilir enerji kaynaklarından da sağlanabilmektedir. Fosil yakıtların tükeniyor olması ile birlikte yenilenebilir enerji kaynaklarına olan yönelim daha da artmıştır. Yenilenebilir enerji kaynaklarının en çok tercih edilen çeşiti Güneş enerjisidir. Güneş enerjisinden elektrik üretimi PV panellerle mümkün olmakta ve bu panellerin verimini birçok faktör etkilemektedir. Bu çalışma, fotovoltaik (PV) panel yüzeyinde oluşan kirlenmenin panel performansı üzerindeki etkilerini enerji ve ekserji temelli olarak incelemektedir. Deneysel çalışmalar, Elazığ ili iklim koşullarında Fırat Üniversitesi Makine Mühendisliği Bölümü çatısında kurulan bir test düzeneğinde gerçekleştirilmiştir. Deneylerde aynı özelliklere sahip iki adet 50 W'lık polikristal PV panel kullanılmış; panellerden biri her saat temizlenmiş, diğeri ise kirli bırakılmıştır. Her iki panel için akım, gerilim, güç, panel sıcaklığı, radyasyon, rüzgâr hızı, nem oranı ve dış sıcaklık değerleri eş zamanlı olarak ölçülmüştür. Elde edilen veriler kullanılarak panellerin enerji ve ekserji verimleri hesaplanmış, sonuçlar karşılaştırmalı olarak değerlendirilmiştir. Bulgular, panel yüzeyinde biriken tozun ve kirin güneş ışınımının soğurulmasını engellediğini ve buna bağlı olarak enerji ile ekserji veriminde belirgin düşüşe neden olduğunu göstermiştir. Temiz panelin ortalama enerji verimi kirli panele göre %17,3; ekserji verimi ise yaklaşık %25–30 oranında daha yüksek bulunmuştur. Kirli panelde, artan yüzey sıcaklığına bağlı olarak ısı geçişi ve tersinmezliklerden kaynaklanan ekserji yıkımlarının arttığı tespit edilmiştir. Elde edilen sonuçlar, PV sistemlerin verimliliğini koruyabilmek için periyodik temizlik ve bakım uygulamalarının zorunlu olduğunu, ayrıca sistem değerlendirmelerinde yalnızca enerji değil ekserji analizinin de dikkate alınması gerektiğini ortaya koymaktadır.

Anahtar Kelimeler: *Fotovoltaik Panel, Kirlenme, Ekserji, Enerji.*

EXPERİMENTAL INVESTİGATİON OF THE EFFECT OF CONTAMİNATİON ON PV PANEL SURFACE PERFORMANCE

ABSTRACT

Energy is an important resource whose demand increases as societies grow. Energy can be obtained from fossil fuels as well as renewable energy sources. With the depletion of fossil fuels, the shift towards renewable energy sources has increased. Solar energy is the most preferred type of renewable energy source. Electricity generation from solar energy is possible with PV panels, and many factors affect the efficiency of these panels. This study examines the effects of contamination on the surface of photovoltaic (PV) panels on panel performance based on energy and exergy. Experimental studies were conducted in a test setup installed on the roof of the Fırat University Department of Mechanical Engineering under the climatic conditions of Elazığ province. Two 50 W polycrystalline PV panels with the same characteristics were used in the experiments; one panel was cleaned every hour, while the other was left dirty. Current, voltage, power, panel temperature, radiation, wind speed, humidity, and ambient temperature values were measured simultaneously for both panels. The energy and exergy efficiencies of the panels were calculated using the obtained data, and the results were evaluated comparatively. The findings showed that dust and dirt accumulated on the panel surface prevented the absorption of solar radiation, causing a significant decrease in energy and exergy efficiency. The average energy efficiency of the clean panel was found to be 17.3% higher than that of the dirty panel, while its exergy efficiency was approximately 25–30% higher. In the dirty panel, an increase in exergy destruction due to heat transfer and irreversibilities associated with increased surface temperature was observed. The results obtained reveal that periodic cleaning and maintenance are essential to maintain the efficiency of PV systems and that exergy analysis, not just energy, should be considered in system evaluations.

Keywords: Photovoltaic Panel, Contamination, Exergy, Energy.

1. GİRİŞ

Günümüzde küresel enerji talebi, ekonomik büyüme, sanayileşme ve nüfus artışı ile birlikte hızla yükselmektedir (IEA, 2024). Bu artış fosil yakıt kullanımını da beraberinde getirerek karbon emisyonlarının yükselmesine, hava kirlenmesine ve iklim değişikliğinin şiddetlenmesine yol açmaktadır (IEA, 2024; Reuters, 2024). Bu olgular, enerji sistemlerinde dönüşümü kaçınılmaz kılmakta ve yenilenebilir enerji kaynaklarına yönelimi teşvik etmektedir. Uluslararası Enerji Ajansı'nın "Renewables 2024" raporuna göre, 2024-2030 döneminde yenilenebilir kapasitedeki büyümenin %80'inin güneş (PV) kaynaklarından gelmesi beklenmektedir (IEA, 2024). Küresel ölçekte, 2024 yılı itibarıyla güneş ve rüzgâr enerji üretimi, hidroelektrik üretimini geride bırakmış ve güneş enerjisi 2030'a kadar en baskın yenilenebilir kaynak haline gelme yolundadır (IEA, 2024; IEA, 2024, Global Overview). Türkiye açısından bakıldığında, ülkemiz yüksek güneş potansiyeline sahip olmasına rağmen bu potansiyel henüz tam olarak değerlendirilememiştir (Dinçer, 2011; TİSEJ, 2019). Türkiyenin Güneş enerjisi potansiyeli haritası Görsel 1.'de verilmiştir.



Görsel 1. Türkiye'nin Fotovoltaik Güç Potansiyeli Haritası

2024 yılında Türkiye'de rüzgar ve güneşten elde edilen elektrik üretimi, yerli kömürden gelen üretimi geride bırakmış, güneş enerjisinin payı %7,5'e yükselmiştir (Dünya Enerji, 2025). Bu doğrultuda, Türkiye'nin enerji stratejileri hem arz güvenliğini sağlamak hem de karbon salınımını azaltmak amacıyla güneş enerjisinin yaygınlaştırılmasını hedeflemektedir (Eurasian Research, 2024). Deneylerin gerçekleştirildiği Elazığ ili, Doğu Anadolu Bölgesi'nde yer almasına rağmen güneş enerjisi açısından avantaja sahiptir. Örneğin, 1.036,8 kWp kapasiteli bir fotovoltaik santral ile yapılan performans analizinde, Ocak-Temmuz 2018 döneminde sistemin verimliliği ile PV*SOL simülasyon sonuçları arasındaki farkın düşük olduğu (yaklaşık %0,03) tespit edilmiştir (Özdemir & Çelik, 2025)

Güneş enerjisinden elektrik üretimi, güneş ışınımının doğrudan elektrik enerjisine dönüştürülmesi esasına dayanır. Bu dönüşüm, fotovoltaik (PV) hücreler aracılığıyla gerçekleşir; hücrelerde bulunan yarı iletken malzemeler (çoğunlukla silisyum), güneş ışığına maruz kaldığında fotoelektrik etki sayesinde elektronları serbest bırakarak bir elektrik akımı oluşturur (Kalogirou, 2014). Bu sistemlerde modül yapısı, eğim açısı, yönelme, sıcaklık, ışınım şiddeti ve kirlenme (toz, kuş pisliği vb.) gibi çevresel ve fiziksel faktörler verimi doğrudan

etkiler (Hassan ve ark., 2022). Özellikle yüzey kirliliği, gelen ışınımın panele ulaşmasını engelleyerek enerji üretiminde ciddi kayıplara neden olabilir; yapılan çalışmalar, uzun süre temizlenmeyen panellerde %25–40'a varan verim düşüşleri bildirmiştir (Saidan ve ark., 2020). Ayrıca panel sıcaklığının artması, yarı iletkenlerin iç direncini yükselterek çıkış gücünü azaltır; bu nedenle soğutma sistemleri, uygun eğim ve havalandırma tasarımı verim artışı açısından önemlidir (Sarver ve ark 2013). Dolayısıyla güneş enerjisinden maksimum elektrik üretimi için çevresel koşulların doğru analiz edilmesi, panel malzemesinin seçimi ve düzenli bakım uygulamaları hayati önem taşımaktadır. Son zamanlarda yapay zekanın neredeyse bütün alanlarda yaygın olarak kullanıldığı bilinmektedir. Güneş panellerinin optimizasyonu yapay zekanın etkili kullanımı sonucunda mümkün olmaktadır. Bu konuda literatürde birçok kıymetli çalışma mevcuttur bunlar aşağıda verilmiştir.

Karagözoğlu ve arkadaşları (2023), fotovoltaik (PV) sistemlerde yapay sinir ağı (YSA) tabanlı bir maksimum güç noktası izleme (MPPT) simülasyonu geliştirerek değişken çevre koşullarında sistemin tepkisini incelemiştir. Çalışmada ışınım ve sıcaklık giriş parametreleri olarak kullanılmış, Levenberg–Marquardt algoritmasıyla eğitilen ağın klasik MPPT yöntemlerine kıyasla daha hızlı yakınsama ve yaklaşık %98 verim sağladığı belirlenmiştir. Bulgular, YSA tabanlı yaklaşımın dalgalı ışınım ve sıcaklık koşullarında güç salınımlarını azaltarak izleme kararlılığını artırdığını göstermiştir.

Kapucu ve arkadaşları (2019), ise Ege Üniversitesi Güneş Enerjisi Enstitüsü verilerini kullanarak, topluluk (ensemble) öğrenmesi temelli bir arıza tespit modeli önermiştir. Muğla'daki konut tipi bir PV kurulumundan elde edilen elektriksel ve meteorolojik veriler üzerinde yapılan analizlerde, sistemin kısmi gölgelenme **ve** kısa devre gibi arızaları yüksek doğruluk oranlarıyla sınıflandırabildiği görülmüştür. Model, Python/Scikit-learn ortamında optimize edilerek tekil algoritmalara kıyasla daha yüksek genelleme başarımı sunmuştur.

Uğuz ve arkadaşları (2019), tarafından yürütülen bir diğer çalışmada, Türkiye'nin farklı coğrafi bölgelerinde PV sistemlerinden elde edilebilecek güç üretiminin makine öğrenmesi (ML) tabanlı yöntemlerle tahmini amaçlanmıştır. NASA meteorolojik girdileri ve RETScreen temelli parametreler kullanılarak çoklu regresyon, yapay sinir ağı ve diğer yöntemlerin karşılaştırıldığı araştırmada, ML modellerinin kısa ve orta vadeli güç tahminlerinde başarılı performans sergilediği ve PV sistem tasarımı için karar destek potansiyeli taşıdığı sonucuna varılmıştır.

Eryılmaz ve arkadaşları (2023), tarafından yapılan çalışmada, Dicle Üniversitesi kampüsündeki PV istasyonu verileri kullanılarak GD-RVFLN (Gürbüz Düzenlenmiş Rastgele Vektör Fonksiyonel Bağlantı Ağı) modeli geliştirilmiştir. Bu model, 10 dakikalık zaman aralıklarında kısa dönem PV güç tahmini yapabilmiş ve 11 farklı modelle kıyaslandığında daha yüksek doğruluk ve hızlı öğrenme kapasitesi göstermiştir. Sonuçlar, önerilen yöntemin şebeke entegrasyonu ve işletme planlaması için önemli bir araç olabileceğini ortaya koymuştur.

Savaş ve arkadaşları (2023), ise güneş enerji santrallerinde yapay zekâ destekli bakım-onarım sistemine odaklanmış; sensör verilerinin analitiği, arıza tespiti ve öngörücü bakım yaklaşımlarıyla kapasite kullanım oranının artırılabileceğini belirtmiştir. Çalışma, saha operasyonlarının dijitalleşmesi ve bakım süreçlerinin otomasyonu için bütüncül bir yapay zekâ çerçevesi önermektedir.

Bahaidarah ve çalışma arkadaşları (2013), sıcak iklim koşullarında fotovoltaik (PV) modüllerin arka yüzeyine entegre edilen su soğutma sistemlerinin performans üzerindeki etkisini deneysel olarak incelemiştir. Bulgular, su sirkülasyonunun panel yüzey sıcaklığını yaklaşık 20 °C oranında düşürdüğünü ve bu sayede sistem veriminin %10–15 arasında

iyileştiğini göstermektedir. Bu sonuç, özellikle yüksek sıcaklık bölgelerinde PV modül verimliliğini artırmak için etkin bir aktif soğutma stratejisinin uygulanabileceğini ortaya koymaktadır.

Kalogirou (2014), tarafından yapılan araştırmada, faz değişim malzemesi (PCM) kullanılarak gerçekleştirilen pasif soğutma yöntemlerinin enerji tüketimi olmadan modül sıcaklığını dengelemede etkili olduğu ifade edilmiştir. Bu yaklaşım, PV sistemlerinde uzun vadeli performans kararlılığı ve sürdürülebilir soğutma açısından çevre dostu bir çözüm olarak öne çıkmaktadır.

Seme ve arkadaşları (2019), tarafından yürütülen teknik-ekonomik karşılaştırma çalışmasında, tek ve çift eksenli güneş izleme sistemleri analiz edilmiştir. Çalışma bulguları, çift eksenli izleme sistemlerinin sabit eğimli panellere göre yıllık enerji üretimini yaklaşık %30**,** tek eksenli sistemlerin ise %15–25 oranında artırdığını ortaya koymuştur. Bununla birlikte, yazarlar bu tür sistemlerin yüksek yatırım maliyetlerine sahip olduğunu, dolayısıyla ekonomik uygulanabilirliğin sistem ölçeği ve yerel koşullara göre dikkatle değerlendirilmesi gerektiğini vurgulamıştır.

Bu çalışma Elazığ iklim koşullarında gerçekleşmiş olup yapılan deneylerde 2 adet polikristal panel kullanılmıştır. Yapılan deneyler 4 gün sürmüş panellerden biri bir saatlik aralıklarla temizlenmiş diğeri ise kirli bırakılmıştır. 2 panelden de eş zamanlı olarak akım, gerilim, güç, sıcaklık ve radyasyon ölçümleri alınmıştır. Bunların yanında dış sıcaklık, rüzgar hızı, nem oranı parametreleri kaydedilmiştir. Alınan verilerle panellerin enerji ekserji verimi hesaplanmış ve deney sonuçları karşılaştırılmıştır.

2. Materyal ve Metod

Deneysel çalışmalar Elazığ İli iklim şartlarında Fırat Üniversitesi Makine Mühendisliği bölümü çatısında kurulan deney düzeneğinde gerçekleştirilmiştir. Yapılan deneyler 4 gün sürmüştür ve deneyler 09:10- 16:00 saatleri arasında gerçekleştirilmiştir. Deneylerde 2 adet Polikristal PV Panel kullanılmıştır. Deney setinin görüntüsü Görsel 2-3.'de verilmiştir.



Görsel 2. Saatte Bir Temizlenen PV Panel



Görsel 3. Kirli Bırakılan PV Panel

PV Panellerin özellikleri Çizelge 1.'de verilmiştir.

Çizelge 1. Deneylerde Kullanılan Güneş Panellerinin Özellikleri

Güneş Paneli Cinsi	Özellikleri
Polikristal Solar Panel Sistemi (2 adet)	50 Watt Polikristal Solar Panel 110x220x30mm, maksimum voltaj 41.9V, MPPT current 13.05 A

PV Panellerden birisi deney süresi boyunca kirli bırakılırken diğeri 1 saat aralıklarla temizlenmiştir. PV Panellerden eş zamanlı olarak akım, gerilim, güç, panel sıcaklığı, radyasyon, dış sıcaklık, nem oranı, rüzgar hızı parametreleri 10 dakikalık aralıklarla kayıt altına alınmıştır. Görsel 4.'de deneylerde yapılan yüzey sıcaklık ölçümü yapılan IR Testo cihazı ve Görsel 5.'de panele doğrudan bağlanan akım gerilim ve güç ölçümü yapılan solar multimetre cihazı verilmiştir.



Görsel 4. IR Testo



Görsel 5. Solar Multimetre

Deneylerde kullanılan ölçüm aletleri ve özellikleri Çizelge 2.'de verilmiştir.

Çizelge 2. Deneylerde Kullanılan Ölçüm Aletleri ve Özellikleri

Parametre	Ölçüm Cihazı	Belirsizlik Değeri
Nem	Termo-higrometre	±%1
Hava Hızı	Dijital anemometre	±0.1 m/s
Sıcaklık Dağılımı	IR Testo (-20 °C - 100 °C)	±1 °C
Solar radyasyon	Pyrometre	±0.1 Wm^{-2}
Elektriksel Güç	Solar Multimetre	±0.1 Watt

2.1 Hesaplama Prosedürü

2.1.1 Enerji Analizi

PV panelin enerji verimi panele gelen toplam güneş enerjisine kıyasla panelin ürettiği elektrik enerjisini ifade eder.PV Panel enerji verimi Denklem 1.' de verilmiştir.

P: Güç

A: Panel Yüzey Alanı

G: Solar Radyasyon

$$\eta_{en} = \frac{P}{A \cdot G} \tag{1}$$

2.1.2 EkserjiAnalizi

Fotovoltaik sistemde dış kaynaktan gelen tek ekserji akışı, panel yüzeyine ulaşan güneş ışınımının ekserjisidir. Bu giriş ekserjisinin büyüklüğü, ortam sıcaklığı, güneşin etkin sıcaklığı ve yüzeye ulaşan güneş radyasyonu değerlerine bağlı olarak değişmektedir. İlgili ekserji değeri, Denklem 2. kullanılarak hesaplanmıştır. (Petela,1964)

$$\dot{E}x_{sol,pv} = A_{PV}\, G\, [1 + \frac{1}{3} * \left(\frac{T_a}{T_{sun}}\right)^4 - \frac{4}{3}" * (\frac{T_a}{T_{sun}})] \quad (kWh) \tag{2}$$

Bu denklemde Ta ve Tsun sırasıyla ortalama çevre sıcaklığını ve güneşin etkin sıcaklığını göstermektedir. Güneş sıcaklığı hesaplamalarda 6000 K olarak kabul edilmiştir. Elektrik enerjisi, herhangi bir sistemde doğrudan ekserjiye eşdeğer olduğundan, PV panelde üretilen elektrik enerjisi de sistemin ekserji çıktısını temsil etmektedir. Dolayısıyla panelin maksimum elektriksel iş potansiyeli, çevre koşullarına bağlı olarak belirlenen ekserji değeriyle ifade edilmekte ve bu değer Denklem 3. kullanılarak hesaplanmaktadır.

$$\dot{E}x_{elek,PV} = V_{OC}^{*} * I_{SC}^{*} \quad (kWh) \tag{3}$$

Güneş enerjisinin elektrik enerjisine dönüşümü esnasında oluşan ekserji yıkımı Denklem 4 ile hesaplanmıştır.

$$\dot{E}x_{D,conv} = \dot{E}x_{soll} - \dot{E}x_{elec,PV} \tag{4}$$

Isı transferi ile oluşan ekserji yıkımı Denklem 5 ile hesaplanmıştır.

$$\dot{E}x_{D,therm} = \dot{Q} * \left(1 - \frac{T_{amb}}{T_{cell}}\right) \tag{5}$$

Bu denklemde Q, Tamb ve Tcell sırayla çevreye olan ısı kaybını, ortalama çevre sıcaklığını ve panel sıcaklığını ifade eder. Panel yüzeyinden çevreye olan ısı kaybı Denklem 6 ile hesaplanmıştır.

$$\dot{Q} = U * A_{PV} * (T_{cell} - T_{amb}) = (h_{conv} + h_{rad}) * A_{PV} * (T_{cell} - T_a) \tag{6}$$

Bu denklemde U toplam ısı transferi katsayını ifade eder ve U konveksiyon ve radyasyon katsayılarının toplamıyla elde edilir. Konveksiyon ısı transfer katsayısı denklem 7 ile hesaplanmıştır. (Bayrak ve diğerleri, 2017)

$$h_{conv} = 2.8 + 3 * V_W \quad (W/m^2\,°C) \tag{7}$$

Bu denklemde Vw saatlik ortalama rüzgar hızını ifade etmektedir.PV ve çevre arasında ışınım transfer katsayısı denklem 8 ile hesaplanmıştır.

$$h_{rad} = \varepsilon * \sigma * (T_{sky} - T_{cell}) * (T_{sky}^{\,2} - T_{cell}^{\,2}) \qquad (W/m^2\,°C) \tag{8}$$

Burada ε ve σ sırayla emisyon ve Stefan- Boltzmann sabitini ifade eder. Bu denklemde kullanılan gökyüzü sıcaklığı Denklem 9 kullanılarak hesaplanmıştır.

$$T_{sky} = T_{amb} - 6 \quad (°C) \tag{9}$$

Pv panelden ekserji çıkış değeri Denklem 10 kullanılarak hesaplanmıştır.

$$\dot{E}x_{out,PV} = \dot{E}x_{soll} - \dot{E}x_{dest,conv} - \dot{E}x_{dest,elek} - \dot{E}x_{dest,therm} = P_{max}^{\,*} - \dot{E}x_{dest,therm} \tag{10}$$

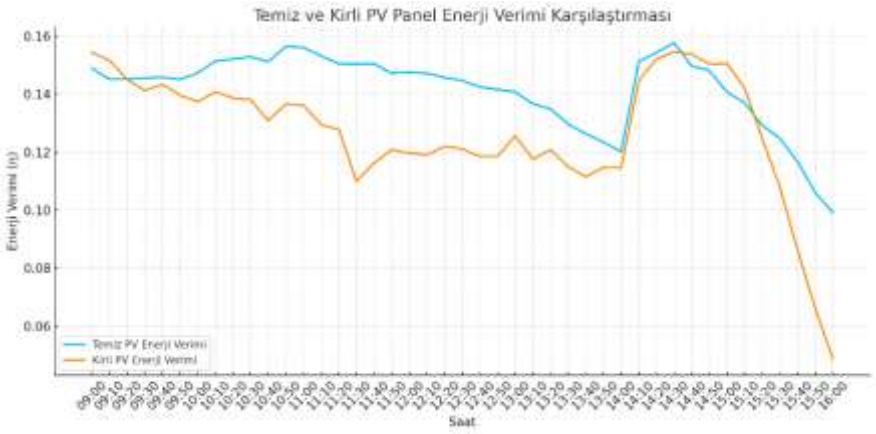
PV panelin ekserji verimi denklem 11 kullanılarak hesaplanmıştır.

$$\Psi_{PV} = \frac{Ex_{out,pv}}{Ex_{sol,pv}} = \frac{P_{max}^{\,*} - \dot{E}x_{D,therm}}{Ex_{sol,pv}} \tag{11}$$

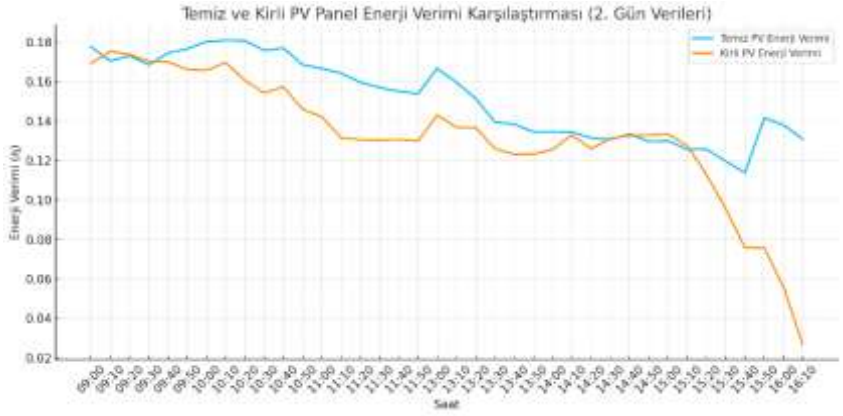
3. BULGULAR

Yapılan deneylerde temiz PV panel performansı ve kirli PV panel performansı karşılaştırılmış ve temiz PV panelin %17,3 daha verimli olduğu sonucuna ulaşılmıştır.

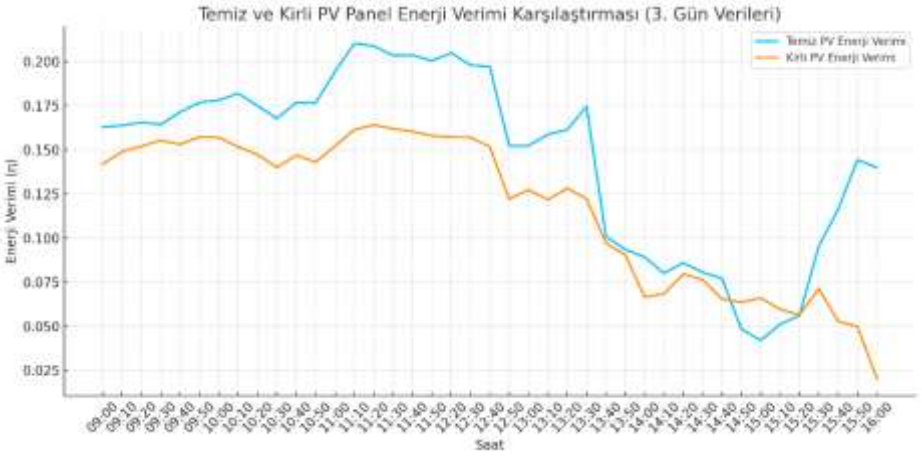
PV Panellerin deney yapılan tüm günler için enerji verimliliği karşılaştırma grafiği Görsel 6-9. arasında verilmiştir.



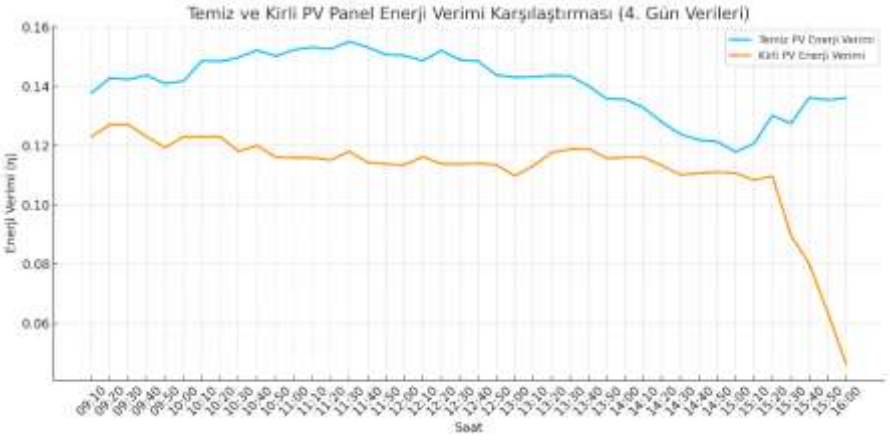
Görsel 6. 1. Gün PV Panel Enerji Verimliliği Karşılaştırma Grafiği



Görsel 7. 2. Gün PV Panel Enerji Verimliliği Karşılaştırma Grafiği



Görsel 8. 3. Gün PV Panel Enerji Verimliliği Karşılaştırma Grafiği



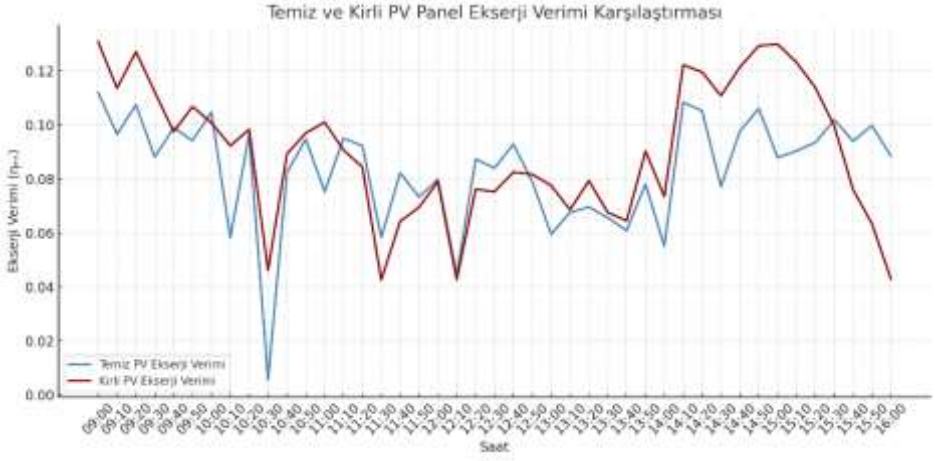
Görsel 9. 4. Gün PV Panel Enerji Verimliliği Karşılaştırma Grafiği

Grafiklerdeki mavi çizgi temiz PV panelin enerji verimliliğini, turuncu çizgi ise kirli (tozlu) PV panelin enerji verimliliğini göstermektedir. Tüm günler için ortak eğilim, kirli panelin verim değerlerinin temiz panele göre belirgin biçimde düşük olmasıdır. Bu fark, gün ilerledikçe ve panel yüzeyinde sıcaklık ve toz birikimi arttıkça daha da belirginleşmektedir. Toz birikimi, panel yüzeyine düşen güneş ışığının bir kısmının emilmeden yansımasına neden olarak absorbe

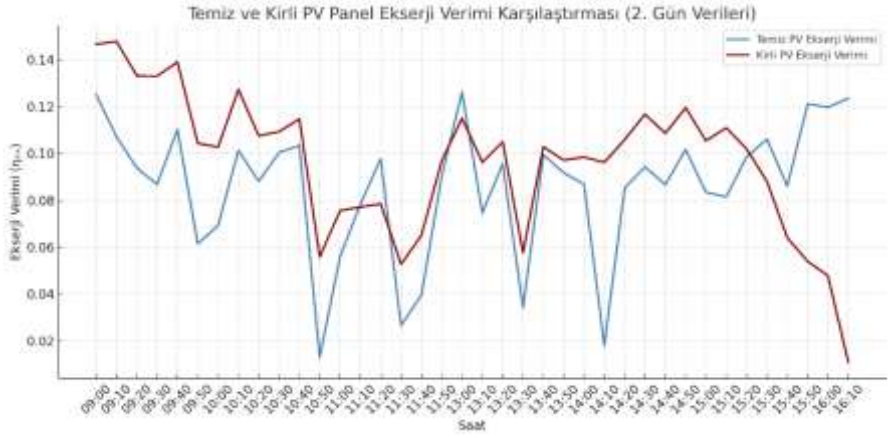
edilen radyasyon miktarını azaltır. Bu durum, özellikle öğle saatlerinde hücre sıcaklığı artışıyla birleştiğinde panelin dönüştürme verimini düşürmektedir.

Bu dört günlük gözlem sonucunda: Tozlanmanın artışıyla PV panel enerji verimi sürekli olarak azalmaktadır. Verim kaybı günlük ortalama %5–10 düzeyindedir. Dördüncü gün sonunda, kirli panelin enerji üretimi temiz panele göre yaklaşık %15-20 oranında daha düşüktür. Bu bulgular, periyodik temizlik veya kirlilik eşiğine dayalı bakım planlamasının PV sistem performansını korumak açısından zorunlu olduğunu göstermektedir.

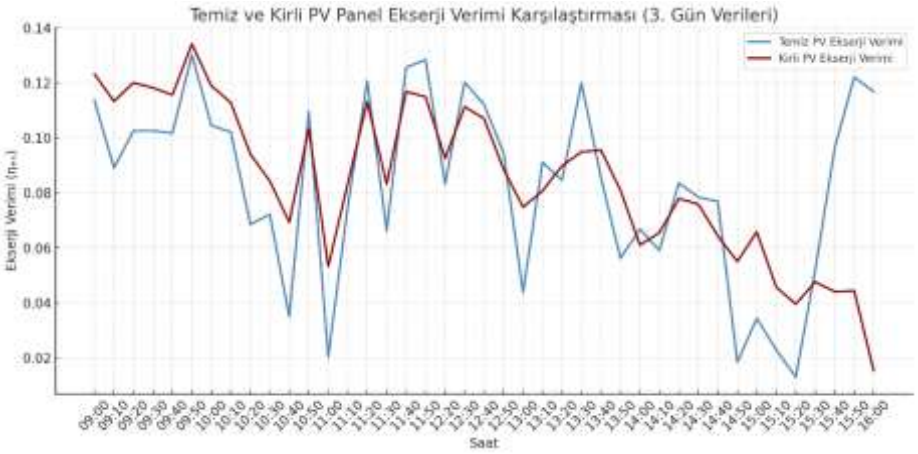
Ekserji verimliği karşılaştırma grafikleri de Görsel 10-13. aralığında verilmiştir.



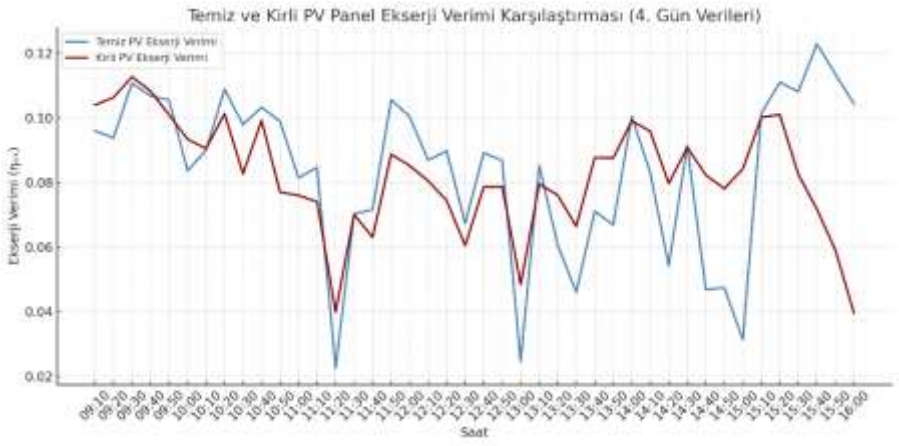
Görsel 10. 1. Gün PV Panel Ekserji Verimliliği Karşılaştırma Grafiği



Görsel 11. 2. Gün PV Panel Ekserji Verimliliği Karşılaştırma Grafiği



Görsel 12. 3. Gün PV Panel Ekserji Verimliliği Karşılaştırma Grafiği



Görsel 13. 4. Gün PV Panel Ekserji Verimliliği Karşılaştırma Grafiği

Tüm grafiklerde mavi çizgi temiz PV panelin ekserji verimini, bordo çizgi ise kirli PV panelin ekserji verimini göstermektedir. Dört gün boyunca her iki panelde de ekserji verimliliği %3–15 aralığında değişmiş; grafiklerdeki belirgin dalgalanmalar anlık ışınım, sıcaklık ve rüzgâr hızı değişimlerinden kaynaklanmıştır. Kirli panellerde, enerji verimliliği kadar olmasa da ekserji kayıpları gözlenmektedir; bu durum, tozun yüzey sıcaklığını artırarak hücre–çevre sıcaklık farkını büyütmesi ve dolayısıyla tersinmezlikleri artırmasıyla açıklanabilir.

Bu dört günlük gözlemlerden şu çıkarımlar yapılabilir: Ekserji verimi, enerji verimine göre daha düşük değerlerdedir çünkü sistemin termodinamik tersinmezlikleri hesaba katılmaktadır. Toz birikimi, yüzey sıcaklığını artırdığı için ekserji yıkımını da artırır. Günler ilerledikçe temiz ve kirli paneller arasındaki fark büyümekte, 4. gün sonunda kirli panelin ortalama ekserji verimi temiz panele göre yaklaşık %15–20 daha düşmektedir. Bu sonuç, PV sistemlerin sadece enerji değil, ekserji bazlı performans değerlendirmesinde de periyodik temizliğin ne kadar önemli olduğunu ortaya koymaktadır.

4. GENEL DEĞERLENDİRME VE SONUÇLAR

Dört günlük deneysel ölçümler sonucunda, temiz ve kirli PV panellerin ekserji verimleri arasında anlamlı farklar tespit edilmiştir. Ortalama olarak temiz panelin ekserji verimi %8–12 aralığında değişirken, kirli panelin verimi %6–9 seviyelerinde kalmıştır. Her iki panelde de gün ilerledikçe düşüş eğilimi gözlenmiş; bu durum, artan hücre sıcaklığının ve buna bağlı ekserji

yıkımlarının (tersinmezliklerin) etkisini göstermektedir. Kirli yüzeye sahip panellerde, ışınımın bir kısmı toz tabakası tarafından soğurulmadan yansıtıldığı için güneş enerjisinin iş potansiyeli (ekserjisi) azalmaktadır. Ayrıca, toz tabakasının oluşturduğu ısıl bariyer nedeniyle panel yüzey sıcaklığı artmakta, bu da çevre–hücre sıcaklık farkını büyüterek ekserji kayıplarını hızlandırmaktadır. Dördüncü gün sonunda kirli panelin ortalama ekserji veriminin temiz panele göre yaklaşık %25–30 oranında daha düşük olduğu saptanmıştır. Bu bulgu, fotovoltaik sistemlerin performans değerlendirmelerinde yalnızca enerji değil, ekserji analizinin de dikkate alınması gerektiğini vurgulamaktadır. .

5. TEŞEKKÜR

Bu çalışmadaki deneyler ‘Olumsuz Çevre Şartlarının Fotovoltaik Panel Verimi Üzerindeki Etkilerinin Görüntü İşleme Yöntemi Yardımıyla İncelenmesi’ isimli yüksek lisans çalışması kapsamında yapılmıştır. Yüksek lisans tezi FÜBAP MF.25.107 numaralı proje tarafından desteklenmektedir.

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ASSESSING URBAN CARBON SEQUESTRATION POTENTIAL USING GIS AND REMOTE SENSING: EVIDENCE FROM RAJSHAHI CITY, BANGLADESH

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ABSTRACT

The rapid increase in urbanization in recent decades has resulted in a substantial worldwide rise in carbon emissions specifically inside metropolitan regions. Rajshahi, a city situated in Bangladesh, has garnered attention for its capacity to serve as a carbon sink. The objective of this study is to precisely assess and measure the carbon storage potential of several carbon sinks present in the city, including water bodies, vegetation, and bare soil. The research aims to estimate the spatial trend and quantify the current carbon storage capacity in each identified carbon sink within Rajshahi city. Additionally, it seeks to identify areas with high carbon sequestration potential, also referred to as carbon sequestration hotspots. This study employs Geographic Information Systems (GIS) and remote sensing techniques to conduct a thorough examination of the capacity for carbon sequestration in Rajshahi. Carbon absorption coefficient values derived from established global and regional were applied to each land cover type to quantify their respective carbon storage and sequestration capacities. The study revealed a notable surge in urban regions and a progressive decline in cool land coverings such as water bodies and vegetation. The urbanization rate experienced a nearly 10% growth from 1992 to 1997, while the extent of vegetative cover declined by almost 1 square kilometer. The results also indicate that bare land (53%) and vegetation (38%) constitute the dominant carbon sinks in Rajshahi City, contributing the highest amounts of above-ground biomass and carbon storage. Spatial analysis further reveals uneven distribution of carbon sinks across the city, with the northern and peripheral zones containing relatively higher biomass density than the central urban core. The study provides a baseline geospatial dataset for policymakers, urban planners, and environmental agencies to develop climate-responsive urban management strategies in rapidly urbanizing contexts.

Keywords: Carbon Sequestration Hotspots, Carbon Sinks, Carbon Stock, Geographic Information System (GIS), Remote Sensing, Land Use/Land Cover (LULC).

1. INTRODUCTION

Over the past few decades, there has been a significant increase in the worldwide urban population, with more than half of the world's people currently living in urban areas (Seto et al., 2012a). The rapid increase in urbanization has resulted in substantial alterations in land utilization, marked by widespread transformations of land into urban zones (Jiang et al., 2012). Efforts to lessen the effects of global environmental change frequently involve extensive plantation initiatives designed to decrease greenhouse gas emissions and improve carbon sequestration (Yang et al., 2020).The assessment of carbon sequestration in these plantations depends on comprehending how different management practices, disturbances, stand ages, and structures in different landscapes impact carbon sequestration rates (Cao et al., 2018). Prior research has conventionally depended on carbon storage information obtained from different tree species under consistent pedoclimatic circumstances (Trum et al., 2011) . Nevertheless, the accuracy of carbon storage calculations can be impeded by errors at the regional level caused by spatial variability (Yang et al., 2020b). A comprehensive comprehension of carbon conservation in several plantations is frequently constrained to evaluations of the carbon balance at a regional level.

Urban areas are frequently portrayed as hubs of ecological degradation, with their adverse effects extending from nearby ecosystems to the global level. Many factors that drive global change can be traced back to these highly populated areas (Strohbach & Haase, 2012). Urban areas are major contributors of greenhouse gases, especially carbon dioxide, which result from a range of activities carried out by city residents, including the use of fossil fuels, industrial manufacturing, high levels of traffic, heating, and cement production. In addition, the process of urbanization disturbs and alters soils and plants, which worsens emissions (Churkina, 2012). Urban areas are therefore involved in various worldwide transformations, such as the rise in carbon dioxide concentrations. Nevertheless, it is important to acknowledge that cities also play a role in providing crucial ecological services, like carbon sequestration. There is increasing concern about the function of urban settings in absorbing carbon and creating carbon sinks, which is being discussed in relation to accountability and attempts to reduce the impacts of climate change (Sohi, 2012).

The primary purpose of this study is to assess and quantify the capacity of the major carbon sinks (such as water body, vegetation and bare land) to sequester carbon dioxide from the atmosphere in the four major urbanized zones of Rajshahi City Corporation (RCC) area namely, City Centre, Eastern Fringe, Western Fringe and Northern Fringe over the past three decades (1992, 1997, 2002, 2007, 2012, 2017 & 2022), which has not been explored till the date following the micro-scale analysis. To fulfill the purpose this particular study (i) Estimated the spatial trend and quantified the current carbon storage capacity/carbon stock in each identified carbon sink within Rajshahi city and (ii) Identified carbon sequestration hotspots/ areas with high carbon sequestration potential in Rajshahi. This particular study has been conducted taking into consideration the hypothesis “There is a robust negative correlation among the rapid changes in LULC and the respective shrinkage of the major carbon sinks”.

2. MATERIALS AND METHODS

To achieve the mentioned objectives, the entire study is divided into three phases. In the first stage of the study preliminary literature about land use and land cover change, carbon sequestration, major carbon sinks, background of the Rajshahi city from the perspective of climatology has been reviewed to select a tentative research topic. Then the goal and objectives of the study has been formulated and study area has been selected based on the research topic. In the second stage comprehensive literature regarding the application of geographic

information systems (GIS) and remote sensing (RS) in land use/land cover (LULC) change detection through satellite image analysis has been reviewed to develop the concept. Secondary data (mainly satellite data) has been collected from the United States Geological Survey (USGS) to calculate the comparative fluctuation of land use/land cover (LULC).

Table 1: Details of the Required Satellite Images

Date Acquired (Year)	Scene ID	Sensor	Cloud Cover	Path/ Row	Spatial Resolution (m)
1992	LT05_L1TP_138043_19920205_201	TM	< 10%	138/43	30
1997	LT05_L1TP_138043_19970306_201				
2002	LT05_L1TP_138043_20010213_201				
2007	L1TP_138043_20070318_20161116				
2012	LT05_L1TP_138043_20110209_201				
2017	LC08_L1TP_138043_20170414_201	OLI			
2022	LC08_L1TP_138043_20220223_202				

Source: USGS Earth Explorer, 2025.

In the last stage, analysis from landsat satellite images and in-depth ground truthing of satellite data has been focused. Based on the spatial and temporal data received from the image analysis, the carbon storage capacity/carbon stock in each identified carbon sink carbon sequestration hotspots/ areas with high carbon sequestration potential in Rajshahi has been identified. Based on the major findings, policy induced recommendations from both the study results and authors have been provided.

In order to evaluate the current carbon storage capacity of the Rajshahi city corporation area, this study takes into account the carbon storage factors (measured in kilograms of carbon per square meter) for vegetation cover, bare ground, and water bodies, as determined by Dorendorf in 2014. The carbon sequestration of Rajshahi city has been determined using Equation (1)

$$CS = \sum_{i=1}^{n} CSi \quad \text{.....(1)}$$

In this study, CS represents the overall carbon storage of Rajshahi city. The variable i refers to the specific storage category, while n represents the total number of storage categories. In this particular study, n is equal to 3, which includes Vegetation Cover, Water Body, and Bare Land. CSi is determined by applying Equation (2)

$$CSi = \sum ASi \times Ei \quad \text{.....(2)}$$

The equation represents the relationship between the total existent area of individual storage type (ASi) and the equivalency factor (Ei). By combining Equations (1) and (2), the calculation of CS may be determined using Equation (3)

$$CS = \sum_{i=1}^{n} (\sum ASi \times Ei) \quad \text{.....(3)}$$

The equations were utilized to calculate the current carbon storage of Rajshahi city, and subsequently, a map illustrating the intensity of carbon storage and the locations with high carbon sequestration rates was generated.

Table 2: Coefficient of Carbon Absorption Factor

Carbon Sink	Coefficient of Absorption Factor (kg of CO_2 /sq. m)	References
Vegetation Cover	0.67	(Dorendorf, 2014; Ghosh et al., 2017; Nowak & Crane, 2002a)
Water Body	1.28	(Taylor et al., 2019)
Bare Land	0.83	(Ghosh et al., 2017)

Source: Author, 2025

3. RESULTS and DISCUSSION

3.1 Temporal Variation of Carbon Absorption

Across the study period, vegetation—which contributes the most to carbon absorption—has experienced a continuous and steep decline. In 1993, vegetation covered about 76.89% of the area and accounted for 74.32% of total carbon absorption. By 2023, vegetation area dropped to 18.33%, absorbing only 37.74% of total carbon. This pattern reflects increasing urban expansion, infrastructure development, and land conversion. Similar trends have been documented in rapidly urbanizing Asian cities, where vegetation loss is strongly associated with declining carbon sequestration and ecosystem quality (Seto et al., 2012b). Studies also show that the loss of tree cover results in disproportionate reductions in carbon uptake because vegetation—especially urban trees serve as the primary carbon sink in cities (Davies et al., 2011; Nowak & Crane, 2002b)

Bare land increased from 12.41% in 1993 to 21.05% in 2023. Interestingly, its share of carbon absorption rose from 14.86% to 53.69%. This rise does not indicate that bare land is becoming more efficient at absorbing carbon. Rather, it reflects the sharp decline in vegetation cover—the main carbon-absorbing class—combined with the relative increase in bare land area. In other words, bare land represents a larger portion of the remaining land, so its percentage share of total carbon absorption increases even though its actual ecological contribution remains low. Urban studies indicate that as vegetated land declines, other land classes—such as built-up or bare surfaces—appear to hold a greater share of ecological functioning simply due to area proportion, not ecological performance (Zhao et al., 2016). Bare land typically stores very little carbon and usually signals land degradation or transition toward construction activities.

Water bodies also show a gradual decrease from 5.86% to 2.18% over 30 years. Correspondingly, carbon absorption from water bodies fell from 10.82% to 8.57%. Shrinking water bodies are commonly linked with urban sprawl, encroachment, and sedimentation problems. Studies in Bangladesh and other South Asian cities show that the reduction of wetlands and water bodies contributes to ecosystem instability and reduced carbon sequestration capacity (Ahmed et al., 2013).Wetlands—although less effective than vegetation—still play a meaningful role in carbon cycling through sediment carbon storage and organic matter accumulation (Table 3).

Table 3: Temporal Variation of Carbon Absorption Capacity

Study Period	Carbon Sink	Area (sq m)	Area (%)	Carbon Absorption	Carbon Absorption (%)
	Water Body	2816100	5.86	3604608	10.82
1993	Vegetation	36950400	76.89	24756768	74.32
	Bare Land	5964300	12.41	4950369	14.86
	Water Body	3324600	6.92	4255488	13.03
1998	Vegetation	26388900	54.92	17680563	54.15
	Bare Land	12912300	26.87	10717209	32.82
	Water Body	2005200	4.17	2566656	9.37
2003	Vegetation	22325400	46.46	14958018	54.58
	Bare Land	11906100	24.78	9882063	36.06
	Water Body	2455200	5.11	3142656	14.73
2008	Vegetation	16767000	34.89	11233890	52.64
	Bare Land	8390700	17.46	6964281	32.63
	Water Body	1563300	3.25	2001024	10.48
2013	Vegetation	14694300	30.58	9845181	51.58
	Bare Land	8722800	18.15	7239924	37.93
	Water Body	1566900	3.26	2005632	11.64
2018	Vegetation	12357000	25.71	8279190	48.04
	Bare Land	8374500	17.43	6950835	40.33
	Water Body	1046700	2.18	1339776	8.57
2023	Vegetation	8806500	18.33	5900355	37.74
	Bare Land	10114200	21.05	8394786	53.69

Source: Author, 2025

3.2 Zone-Specific Carbon Absorption

The table 4 illustrates the differences in carbon absorption capability among certain study zones, namely the City Center, Eastern Fringe, Northern Fringe, and Western Fringe. Each zone is distinguished by its specific land cover composition, which encompasses water bodies, vegetation, and bare land, and their individual roles in absorbing carbon over the study period. Within the City Center, which is marked by urbanization, vegetation covers a relatively lesser fraction of the land compared to bare land. However, it plays a significant role in absorbing carbon, closely followed by bare land. Aquatic ecosystems make a moderate contribution to carbon sequestration in this area. Transitioning to the Eastern Fringe, an area that is between urban and rural environments, the dominant features of the landscape are vegetation and bare land. These elements play a crucial role in absorbing carbon, making a substantial contribution to the process. Water bodies in this zone have a limited impact on carbon absorption. The

Northern Fringe displays a varied terrain with significant vegetation coverage and noteworthy contributions from both vegetation and bare land to carbon sequestration. The contribution of water bodies in this area to carbon absorption is quite insignificant when compared to other types of land cover. The Western Fringe, which combines urban and peri-urban elements, demonstrates a substantial contribution of bare land to carbon absorption, followed by vegetation. The water bodies in this area make a moderate contribution to carbon sequestration. The overall results demonstrate the diverse impacts of different land cover types on carbon sequestration in different regions. Vegetation regularly acts as a significant carbon sink in all areas, but bare ground shows significant potential for absorbing carbon, especially in the Eastern and Western Fringes. Water bodies, although found in all areas, make a relatively small contribution to carbon absorption as a whole.

Table 4: Zone-Specific Carbon Absorption Capacity

Study Zone	Carbon Sink	Area (sq m)	Area (%)	Carbon Absorption	Carbon Absorption (%)
City Center	Water Body	83940	0.65	107444	6.13
	Vegetation	1052867	8.19	705421	40.25
	Bare Land	1132251	8.81	939768	53.62
Eastern Fringe	Water Body	273519	2.07	350104	6.02
	Vegetation	3495871	26.43	2342234	40.25
	Bare Land	3766495	28.48	3126191	53.73
Northern Fringe	Water Body	61171	0.51	78298	1.89
	Vegetation	2570748	21.26	1722401	41.49
	Bare Land	2832291	23.43	2350802	56.63
Western Fringe	Water Body	595297	6.15	761980	22.45
	Vegetation	1502477	15.52	1006660	29.66
	Bare Land	1958433	20.24	1625499	47.89

Source: Author, 2025

3.3 **Carbon Absorption Capacity by Existing Carbon Sink**

The figure provides an evaluation of the carbon absorption potential in different carbon sink categories, specifically Water Body, Vegetation, and Bare Land. Each carbon sink category is assessed according to its ability to sequester carbon dioxide (CO2) in kilograms (kgCO2) and its proportionate contribution to the overall carbon absorption. Water bodies exhibit a moderate potential to absorb carbon, effectively sequestering 1,297,826 kgCO2, representing 9% of the overall carbon absorption. The most notable carbon sink is vegetation, which has a capacity of 5,776,716 kgCO2, accounting for 38% of the overall carbon absorption. The category of bare land demonstrates the greatest ability for carbon absorption, with a total absorption of 8,042,260 kgCO2, accounting for 53% of the overall carbon absorption.

Overall observations suggest that water bodies have a limited impact on carbon absorption, in contrast to vegetation and uncovered land which have a more significant influence. Vegetation,

due to its widespread presence and biological activities, is the main reservoir for carbon, highlighting the significance of conserving and improving wooded regions to promote carbon sequestration initiatives. Barren land, despite its absence of plant life, exhibits significant capacity for carbon absorption, possibly attributable to soil processes and land management techniques.

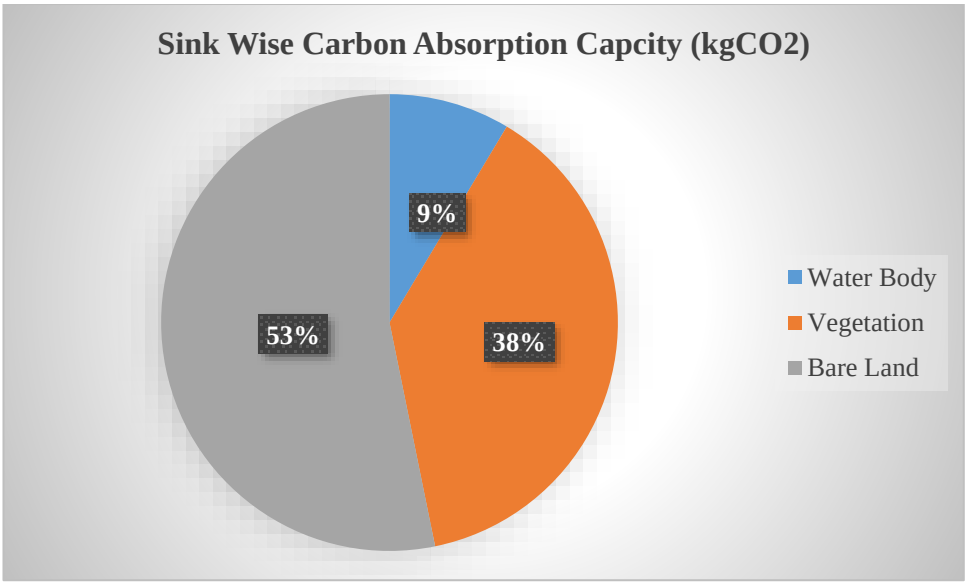

Figure 1: Percentage of Carbon Absorption by Current Carbon Sinks

Source: Prepared by Author, 2025.

The figure presents the carbon absorption capacity (measured in kgCO2/year) of four specific areas of a city: City Center, Eastern Fringe, Northern Fringe, and Western Fringe. The Eastern Fringe has the maximum absorption capacity, specifically 5,818,528.88 kgCO2/year, whereas the Northern Fringe has a little lower capacity of 4,151,501.529 kgCO2/year. By comparison, the City Center can absorb 1,752,632.192 kgCO2 per year, whereas the Western Fringe has a capacity to absorb 3,394,139.106 kgCO2 per year.

The findings indicate substantial disparities in the capacity for carbon absorption among various metropolitan areas, which are likely influenced by factors such as the density of vegetation, land utilization patterns, and environmental circumstances. The significant difference in the ability to absorb carbon highlights the need for focused interventions and urban planning methods to improve carbon sequestration in urban areas.

The variations in carbon absorption capabilities among metropolitan areas emphasize the intricate relationship between urbanization and environmental sustainability. It is essential to address these differences by implementing strategic planning and green infrastructure efforts in order to promote resilient and sustainable cities, reduce the impacts of climate change, and maintain ecological balance in urban environments.

Numerous studies corroborate the trends identified in the carbon absorption distribution throughout Rajshahi City, notably the diminishing influence of vegetation and the escalating prevalence of bare land within the urban carbon budget. Studies on the swiftly expanding cities of South Asia indicate that urban sprawl frequently results in considerable degradation of green cover, thereby markedly diminishing the carbon sequestration potential of urban ecosystems (Dewan & Yamaguchi, 2009). In Bangladesh, analogous trends have been observed in Dhaka, Khulna, and Rajshahi, where vegetated regions have gradually been supplanted by constructed

surfaces and barren land, leading to fragmented green spaces and diminished ecological functionality (Ahmed et al., 2013; Rahman & Hasan, 2024). These literatures collectively underscore that persistent land-cover alterations in Rajshahi are significantly diminishing natural carbon sinks, emphasizing the necessity for strategic urban greening and landscape restoration.

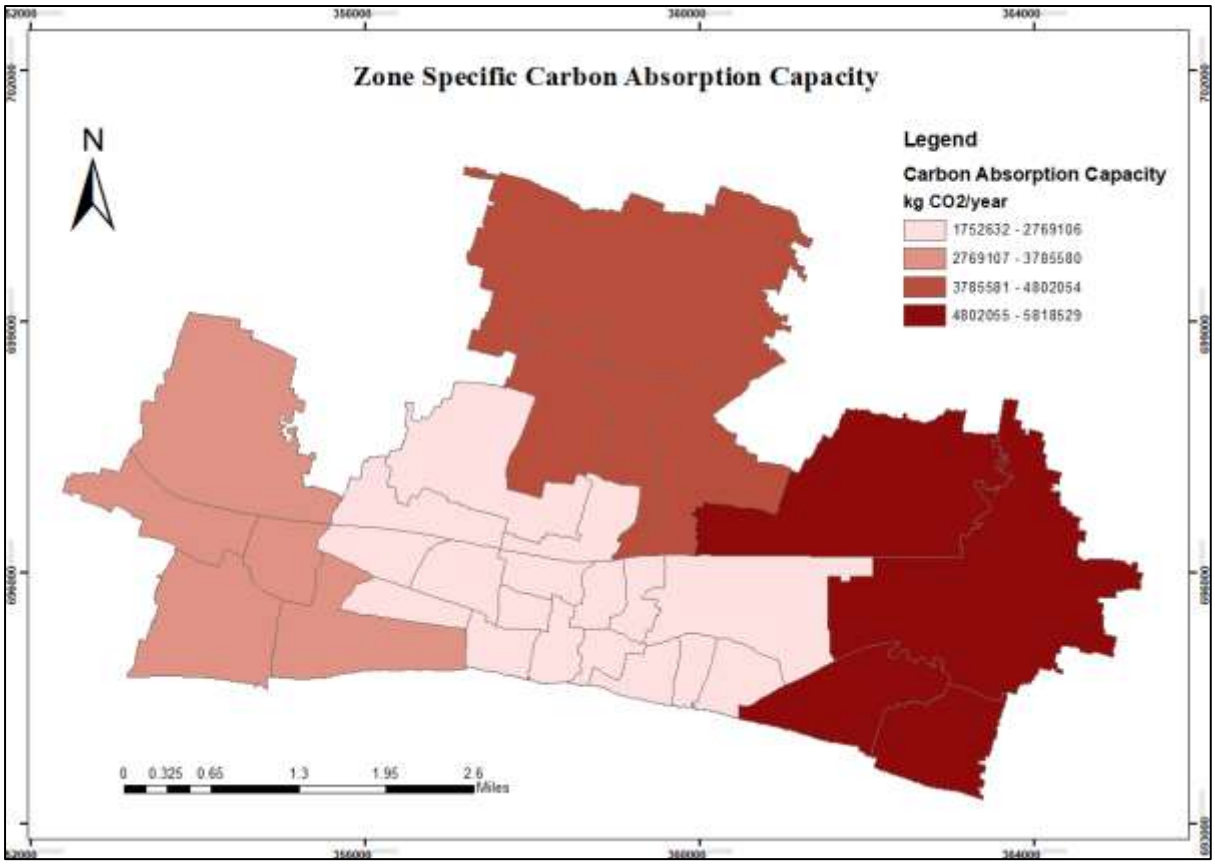

Figure 2: Carbon Absorption Categories of RCC Area.

Source: Prepared by Author, 2025

4. Conclusions and Policy Implication

The exhaustive examination of alterations in land cover and the capacity of carbon absorption during the period of investigation from 1992 to 2022 reveals many significant findings concerning urbanization patterns and the ecological viability within the city under consideration. The observed trends indicate a significant rise in metropolitan areas, resulting in the reduction of green coverings such as vegetation and water bodies. This trend highlights the swift rate of urban growth and its substantial influence on changes in land use. The high degree of urbanization, namely in the City Center and Eastern Fringe areas, presents difficulties for urban planning, environmental management, and the preservation of biodiversity. The decrease in plant cover and reduction in the capacity to absorb carbon highlight the pressing requirement for sustainable land use practices and activities aimed at restoring ecosystems. The results highlight the complex connection between urbanization and environmental sustainability, underlining the significance of well-planned actions and the creation of eco-friendly infrastructure to improve the capture of carbon dioxide and maintain a healthy ecological equilibrium in metropolitan areas. To tackle these difficulties, it is necessary to employ a

variety of disciplines, involve all relevant parties, and develop methods for long-term planning that promote cities that are resilient, enjoyable to live in, and environmentally sustainable.

The findings indicate that the city of Rajshahi requires immediate targeted policy modifications to enhance its carbon storage capacity. To compensate for the decline in vegetation over the years, urban greening initiatives must be prioritized, particularly regarding the planting of trees in public spaces, along streets, and within residential neighborhoods. By preserving existing green spaces and establishing new urban forests or pocket parks, one can enhance local microclimates and increase carbon sequestration. The city should implement more stringent land-use zoning regulations to prevent the conversion of vegetated and wetland areas into developed spaces. Creating ecological conservation zones, particularly adjacent to aquatic environments and peri-urban green belts, may safeguard vital ecosystem services. Policies for the restoration and protection of wetlands are crucial due to the diminishing number of water bodies, as wetlands significantly contribute to carbon cycling and possess flood resilience. Urban development projects may incorporate regulations for green infrastructure, such as rooftop gardens, vertical greenery, and permeable landscapes. This will assist in reducing the carbon emissions associated with rapid construction. Incorporating regular monitoring through geographic information systems and remote sensing is essential for tracking land cover changes, evaluating the effectiveness of implemented policies, and facilitating data-driven urban planning. By implementing these measures collaboratively, Rajshahi will transition to a more ecologically balanced urban environment capable of effectively addressing the impacts of climate change.

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STUDY OF THE FORMATION OF CHEMICAL BURN-ON ON STEEL CASTINGS AND THE USE OF ANTI-BURN PAINTS BASED ON KAOLINITE $AL_2SI_2O_5(OH)_4$

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ABSTRACT

This study investigates the mechanisms of chemical burn-on formation on the surface of steel castings produced in sand molds and proposes the application of an anti-burn-on coating based on kaolinite ($Al_2Si_2O_5(OH)_4$, aluminum silicate). The physico-chemical properties of the developed coating are characterized, demonstrating its effectiveness in minimizing burn-on defects on cast surfaces. The application of this coating significantly improves the surface quality of steel castings and enhances the techno-economic efficiency of the foundry process.

Keywords: burn-on; steel castings; burn-on formation mechanism; anti-burn-on coating; foundry defect prevention.

Introduction

The formation of burn-on deposits during steel sand casting remains a significant challenge, adversely impacting the surface quality of castings. Burn-on refers to a tenacious layer where the casting metal surface fuses with molding sand, forming a crust that is difficult to remove and often necessitates additional finishing operations. This defect—categorized as a surface imperfection—arises from complex physical and chemical interactions between the molten metal (and its oxides) and the mold material. Removing burn-on requires extra labor and material, increasing production costs, and also creates environmental concerns due to the cleaning processes (e.g. abrasive blasting, grinding). During steel casting in sand molds, intense thermal exposure causes the molten metal to adhere firmly to sand grains, leading to a burn-on layer that mars the casting surface and must be mechanically cleaned. Addressing burn-on is vital in both mass production and custom casting, especially for complex geometries or components with strict surface requirements.

Chemical burnt on occurs in castings of alloys with a high melting point as a result of complex reactions between casting metal, its oxides and the mold material. Unlike mechanical burning, the sand grains in the burnt layer are bound mainly by the products of chemical reactions occurring at high temperatures, mainly silicates.

Oxides of alloy components enter the metal-mold interface in two ways: in small quantities - in the form of oxides dissolved in the melt and formed during smelting and filling of the mold, and mainly as a result of oxidation of the hot solidifying surface of the casting. A massive steel casting remains in a hot state longer, and therefore more oxides form on its surface.

It is believed that burn-on does not form in two cases: when the surface of the casting is not oxidized or is very strongly oxidized. Burn-on cannot form on an unoxidized metal surface, since only metal oxides interact with the silica of the mold; interaction of unoxidized metal with silica is unlikely.

For example, in small, rapidly cooling castings, where a thin oxide layer forms on the metal surface, it is sufficient to use a refractory dust or a thin layer of paint to prevent burning-on to prevent direct contact of the metal oxides with the mold silica. It is much more difficult to avoid burning-on on medium-weight castings, where oxides form on the casting surface in larger quantities than on small ones, but still insufficient to obtain an oxide layer of optimal thickness, ensuring the production of an easily removable burn-on.

On thick-walled castings obtained in liquid glass molds without the use of coatings, an easily removable burn-on crust is formed, since steel easily oxidizes and produces a large amount of oxides in the burn-on crust.

FeO formed on the surface of castings has a melting point of 1380° C, so it can remain in a liquid state for quite a long time on the surface of even a crystallized steel casting. Iron oxides wet quartz sand well and, under the action of capillary pressure, easily penetrate into the pores of the casting mold, reacting with silica: the formation of ferrosilicate from iron (II) oxide and silicon dioxide:

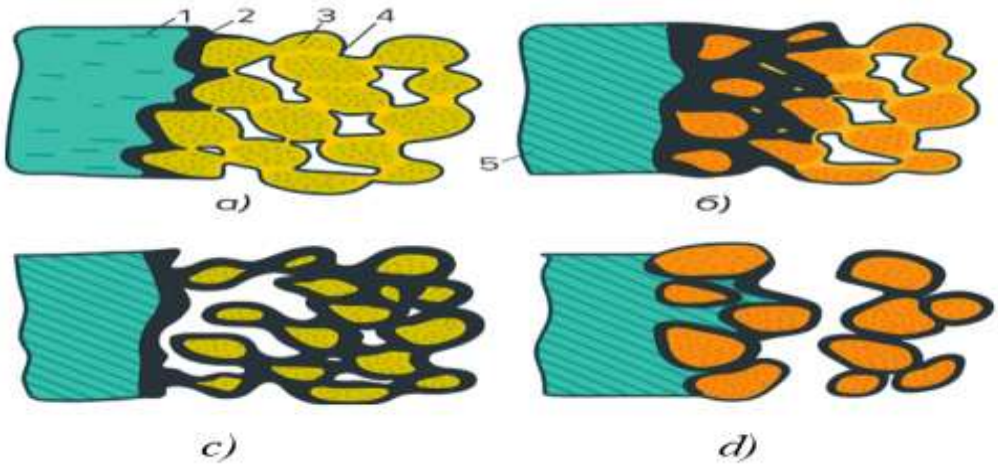
$$2\,FeO + SiO_2 \rightarrow 2\,FeO \cdot SiO_2$$

In alloys with a high manganese content, the formation of burn-on is also promoted by a similar reaction between manganese oxide and silica. As a result, **manganosilicate ($2MnO\ SiO_2$) is formed** - a typical component of slags in ferromanganese smelting and in foundry production.

$$2MnO + SiO_2 \rightarrow 2MnO \cdot SiO_2$$

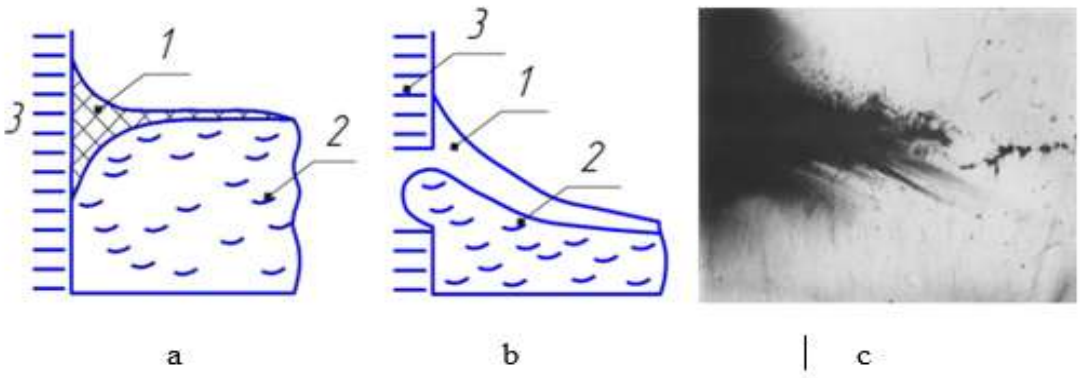
The low-melting silicates fayalite formed as a result of these reactions ($2FeO \cdot SiO_2$) and tephroite **($2MnO \cdot SiO_2$)** after hardening cements sand grains into layers of burnt-on material.

The mechanism of burnt-on formation



Drawing 1. Formation of chemical burnt-on

The formation of chemical burn-on is represented as follows. After pouring the mold, the surface of the casting 1 is covered with a layer 2 of oxides and iron silicates (drawing 1, a: 3 - quartz grains, 4 - film of the fastener). The rate of oxidation of the steel at the first moment after solidification of the casting 5 (Fig. 1, b) in the presence of a large amount of free oxygen in the pores of the mold is high, the resulting oxide melt accumulates in the boundary surface, increasing the relative contact area of the casting and the mold. Some of the melt penetrates deep into the mold between the sand grains, forming and binding the burn-on crust with the casting (see Fig. 1, b). Subsequently, oxidation of the casting surface slows down sharply due to a decrease in the oxidizing capacity of the gases in the mold and a decrease in the temperature of the metal, the rate of formation of a new oxide melt on the boundary surface becomes less than the rate of its migration into the molding mixture, and a gap appears between the casting and the mold (see Fig. 1, c). In this case, the relative area of contact between the metal and the mold decreases see Fig. 1,d). Drawing 2 shows the formation of a burn-on pattern.



Drawing 2. Scheme of formation of burnt-on: 1-burnt-on, 2-liquid metal, 3-sand form ; a- initial stage; b – formation of burnt-on; c – natural appearance of the surface layer of the casting

Recently, the following main ways of preventing chemical burn-on have been considered: protecting the metal in the casting mold from oxidation; creating an oxide film of optimal thickness between the surface of the casting and the burn-on crust in order to obtain an easily separated burn-on; using coatings and molding materials with increased fire resistance and chemically inert to the metal and its oxides. Based on the research results, practical recommendations were developed to prevent burning on carbon steel castings

When producing castings with a wall thickness of up to 10-12 mm, it is more expedient to obtain a poorly developed burn-on stage *a* (see Fig. 1), for which it is necessary to add organic substances to the mixture that form reducing gases (bitumen, fuel oil, coal dust, etc.), slowing down the oxidation of the metal and, consequently, the onset of stage *b* in the structure of the burn-on (see Fig. 1). On castings with walls of 10-35 mm, due to the long time of exposure to high temperature, the process develops to the stage of a hard-to-remove burn-on (see Fig. 1 *b*). Organic additives are already ineffective here, but coatings based on marshalite, alumina, zircon, corundum, aluminum powder again allow obtaining a poorly developed burn-on. Castings with a wall thickness of over 35 mm are obtained with an easily detachable burn-on, since the processes pass to stage *c*. Additives to the mixture that create reducing gases that can delay the development of processes at stage *b* are harmful in this case. Clays, feldspars, slags, etc., that increase viscosity and reduce the rate of migration of the contact melt into the mold, are undesirable. When using sand-clay mixtures for castings with a wall thickness of up to 20-25 mm, clay and dust must be removed from the original sand; the molding mixture must not contain residues of liquid glass mixture, impurities of iron ores, feldspars and other easily sintered fluxes. Additive in a mixture of low-ash substances (fuel oil, bitumen solution) gives positive results. Small 0.2-2% additives to the molding mixture of Mg_2 CO_3, NaCl and other salts, as well as the replacement of clays with bentonites create conditions for obtaining; easily removable burnt-on. It is recommended to cover casting molds with walls of 25-50 mm with paints or pastes based on marshalite, zircon, corundum, etc. How at such thicknesses of castings, a difficult to separate stage occurs: burning *b*(see Fig. 1).

The outer spherical surfaces of castings with walls of 50-70 mm are obtained with easily separated burnt-on (see Fig. 1). Here the shrinkage of the metal and the strength of the mold in a hot state, which is facilitated by the gap, have an effect. The strength of the mold at high temperatures can be increased by adding liquid glass, iron ores and other fluxes to the initial mixture. It is recommended to cover the inner surfaces of such castings with pastes or facings based on zircon, corundum, chrome-magnesite and magnesite.

In forms made of sand-oil and sand-resin mixtures, castings with a wall thickness of up to 15-25 mm are obtained with a poorly developed burn-on. In this case, the sand must be cleaned of clays and other fluxes, and the fasteners must not leave a lot of ash after burning out. Thicker-walled castings should be made using highly refractory coatings of marshalite, zircon (for walls of 30-60 mm) and corundum, chromomagnesite, magnesite (for walls thicker than 60 mm).

When the critical pressure of the metal in the mold is exceeded, either finer-grained sands or special fine-grained highly refractory materials should be used in the form of coatings and facings on the molds. The nature of the atmosphere in the mold after pouring when using The effect of the listed highly refractory materials is less noticeable than when using quartz sand. With an increase in the oxidizing capacity of gases, the refractory resistance of the non-stick coating, especially based on marshalite and zircon, only slightly decreases. Measures to eliminate burning come down to selecting the type of coating depending on the wall thickness. For casting molds with a wall thickness of 20-25 mm, marshalite paints are sufficient. Casting

molds with walls of 25-50 mm require coating with paints or pastes based on alumina, zircon or corundum.

Use of non-stick paints. Radical measures to combat burning include applying silicate-based paint to the surface of the mold. and aluminum **kaolinite** $Al_2 Si_2 O_5 (OH)_4$, pastes and rubs. Kaolinite is a crystalline **clay mineral** that is **a hydrated aluminosilicate.** Aluminum silicate has high heat resistance, is **a refractory filler**, and can withstand temperatures above 1500 °C. It contributes to the smoothness of the casting surface. It is used as a base for water and alcohol suspensions in non-stick coatings applied to molds and rods in metal casting. It forms a dense **heat-protective screen** between the metal melt and the mold. It is chemically inert, does not interact with the metal, preventing **burning.** It is well distributed over the mold surface and creates a smooth protective layer.

As the temperature increases, kaolinite **dehydrates ,** turning into metakaolin, then into mullite and amorphous silica. This leads to **Formation of a dense, ceramic crust** resistant to thermal shock. The resulting layer **reduces the heat flow** from the molten metal to the mold. This **reduces the risk of thermal cracking** and damage to the mold. Kaolinite **does not react with iron, steel, cast iron and alloys ,** preventing the formation of chemical burn-on. The compacted kaolin layer **limits the penetration of metal into the pores of the mold** and protects against sand sintering. After contact with the metal, the kaolin layer **facilitates the removal of the casting ,** reducing the need for cleaning. Additional components for paints are also used, which are shown in Table 1.

Table 1. Components included in the non-stick mixture.

Component	Purpose
aluminum silicate **kaolinite** $Al_2 Si_2 O_5 (OH)_4$.	**aluminosilicate clay** or **kaolin clay .**
Water/alcohol	Dispersion medium (water/alcohol based)
Surfactants	Improves spreadability and wettability
Fine dispersed ceramics	Increases the strength of the coating
Sodium/potassium silicate	A binder that fixes the coating

Highly refractory powders applied to the surface in the form of paints or pastes isolate the grains of quartz sand from contact with the poured metal and prevent its penetration into the pores of the mold. This prevents chemical interaction of quartz with iron oxides and the formation of burn-on. An important criterion for the properties of non-burn-on materials is the degree of their wetting by liquid metal and its oxides.

To prevent burning, the grain base of the coatings is selected so that it is not wetted by the liquid metal and, if possible, its oxides. It must match the poured alloy and the mold material; basic oxides of the alloy cannot be combined with an acidic grain base of the coating and vice versa. It is unacceptable to use two fillers in the paint that can chemically interact with each other. The fire resistance of the paint filler must be higher than the temperature of the poured alloy. Therefore, many industries use paints made of highly refractory materials, despite their high cost, since the increased costs of preparing high-quality coatings are offset by improving

the marketable appearance of castings and reducing the costs of their cleaning. Figure 3 shows the condition of a steel casting before and after using a kaolin-based dye.

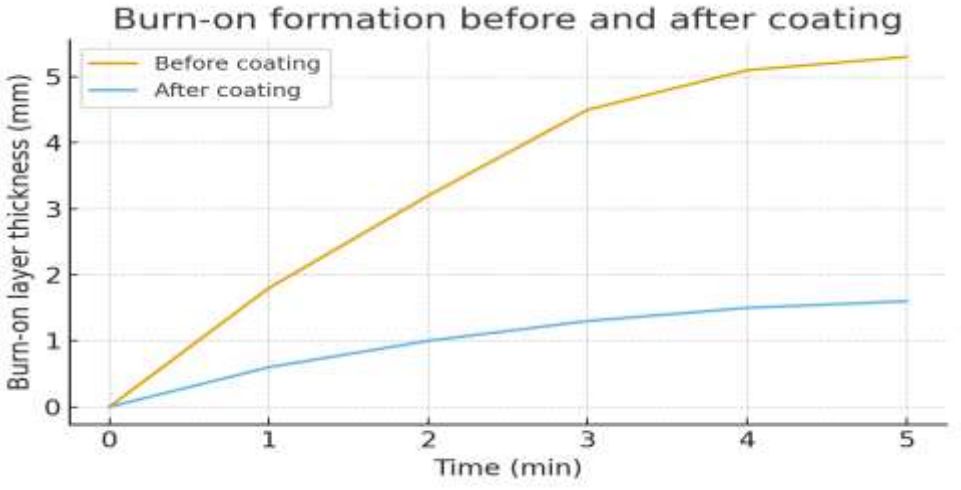


Figure 3. Casting surface before and after application of anti-stick mixture.

The following requirements are imposed on the binders: maximum retention of strength at high pouring temperatures (thermal resistance); thermoplasticity at drying and pouring temperatures; to prevent peeling and cracking of the coating; minimum gas formation.

Therefore, for obtaining castings with a high-quality surface, binding materials with high heat resistance (both organic and inorganic), which minimally interact with iron oxides, are very promising.

In the production of large and thick-walled castings, the surface of the molds is heated to 1000° and more. Therefore, it is necessary to add inorganic binders to the paints, which are distinguished by higher heat resistance than organic ones. These include liquid glass, sulfates, phosphates, etc. A distinctive feature of coatings with phosphate binders is high adhesion strength to the painted surface when pouring metal, low gas-forming capacity, high heat resistance and fire resistance, worsens the wetting of the coatings with metal and its oxides. Graph 1 shows the appearance of burnt food before and after applying a non-stick coating.



At present, there are no universal coatings for casting molds that would give the required effect on all types of casting. All known coatings show their positive effect only in a certain temperature range, with a given composition of the molding mixture and on a specific type of casting. Therefore, along with the paints produced, enterprises produce their own coatings of different compositions for certain types of casting, and they do not go beyond the boundaries

of this enterprise. The main disadvantage of this method is the complication of the technology. Table 2 shows the data after using non-stick paint.

Table: Comparison of casting conditions **before and after application** of aluminum silicate based non-stick paint

Parameter	Before applying paint	After applying paint
Surface type	Rough, with burnt marks	Smooth, clean
Presence of burnt-on residue	Often present (10–50% of area)	Virtually absent (0–5%)
Need for cleaning	High (grinding, sandblasting)	Minimal or none required
Casting defect rate	5-15%	Less than 1%
Labor costs for processing	Elevated	Reduced by 30-50%
Material consumption	Uncoated: up to 5% for cleaning	Coated: savings in the production cycle
Casting extraction speed	Delays due to sticking	Quick Extraction
Mold/core life	Reduced due to aggressive contact	Increased by a protective layer

Conclusion

This study examined the mechanism of chemical burn-on formation in disposable sand casting molds. Scientific investigations have demonstrated that burn-on is a dense, adherent layer formed on the surface of steel castings as a result of high-temperature chemical interaction between metal oxides (FeO, MnO) and silica (SiO_2) present in the molding sand. During casting, the surface of the steel undergoes oxidation, leading to the formation of liquid iron oxides (FeO), which exhibit high wettability with quartz sand. This phenomenon results in the penetration of oxides into the mold structure, cementing the sand grains and forming a persistent surface defect known as burn-on.Burn-on significantly deteriorates the surface quality, dimensional accuracy, and integrity of steel castings. Various methods, protective coatings, and additives are employed in foundry practice to minimize or eliminate this defect.

The article focuses on the application of an anti-stick coating based on aluminum silicate — kaolinite ($Al_2Si_2O_5(OH)_4$) — applied to the surface of disposable sand molds. Kaolinite has proven to be effective in reducing chemical burn-on, enhancing casting quality, lowering production costs, and forming a thermally stable and chemically inert barrier between the molten metal and the mold material.

Аннотация. В данной работе исследованы механизмы образования химического пригара на поверхности стальных отливок при формовании в песчаные формы и предложено противопригарное покрытие на основе каолинита ($Al_2Si_2O_5(OH)_4$, силиката алюминия). Охарактеризованы физико-химические свойства разработанного покрытия, показывающие его эффективность в минимизации образования пригара на отливках. Применение данного покрытия повышает качество поверхности стальных отливок и повышает технико-экономическую эффективность литейного производства,

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BEYOND SPECIES: AN INTEGRATED APPROACH TO BIOLOGICAL RESOURCE MANAGEMENT IN BIODIVERSITY HOTSPOTS

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ABSTRACT

In the context of a global extinction crisis occurring at an unprecedented rate, traditional conservation strategies focusing on single species are increasingly revealing fundamental limitations in addressing complex, systemic drivers of degradation. This research report, titled “Beyond Species,” conducts a comprehensive Systematic Literature Review (SLR) on the paradigm shift toward Integrated Landscape Management (ILM) and ecosystem-based approaches in biodiversity hotspots, with a specific focus on Vietnam and Southeast Asia. Based on a synthesis of hundreds of academic papers, technical reports, and field data from the 2015–2025 period, this study delves into five key pillars: the rationale for the paradigm shift, the technological revolution in monitoring, the effectiveness of community governance models, ecological financial mechanisms, and national policy frameworks. Findings indicate that while species-focused approaches remain foundational for urgent recovery goals, long-term sustainability requires managing “functional biodiversity” and ecological processes (such as gene flow and nutrient cycling) beyond the boundaries of isolated protected areas. In Vietnam, the Payment for Forest Environmental Services (PFES) mechanism has achieved significant financial success but faces major challenges regarding "additionality" and actual conservation effectiveness due to a lack of strong linkages with biodiversity indicators. Simultaneously, the explosion of advanced monitoring technologies such as environmental DNA (eDNA) and Artificial Intelligence (AI) is ushering in an era of biological data transparency, enabling the detection of cryptic species and automating big data analysis. However, barriers regarding technical capacity and a lack of standardized reference libraries are stifling this potential. The report concludes that to achieve the goals of the Kunming-Montreal Global Biodiversity Framework by 2030, Vietnam needs a structural transformation: from fragmented administrative management to integrated governance, institutionalizing the

role of community co-management, and applying digital technology to quantify the true value of "natural capital."

Keywords: Integrated Landscape Management (ILM), Biodiversity Hotspots, Environmental DNA (eDNA), Artificial Intelligence (AI), Payment for Ecosystem Services (PFES), Vietnam.

1. INTRODUCTION: THE URGENCY OF A NEW PARADIGM

1.1. The Anthropocene context and biodiversity crisis

We are living in the Anthropocene, a geological epoch where human activity has become the dominant force shaping the Earth's biological and geographical systems. One of the most tragic characteristics of this era is the catastrophic decline of global biodiversity, often referred to as the "Sixth Mass Extinction." Unlike previous extinction events caused by natural disasters, the current crisis is driven by a combination of factors, including land-use change, overexploitation of resources, climate change, pollution, and the invasion of alien species (Tobias et al., 2025).

For decades, the dominant conservation model was "Fortress Conservation," which focused on strictly zoning protected areas to separate nature from humans, often prioritizing the protection of charismatic megafauna, such as tigers, elephants, or rhinos. While this model has prevented the extinction of certain specific species, it has increasingly proven insufficient in dealing with systemic and transboundary threats. Focusing solely on lists of threatened species (like the IUCN Red List) while ignoring complex ecological interaction networks—known as "functional biodiversity"—is leading to "empty forests," where trees remain, but the animals performing ecological functions (such as seed dispersal, pollination) have vanished (Tilker et al., 2019).

The concept of "Beyond Species" emerges from this context. It does not deny the importance of species protection but proposes a scaling up of management: from individuals to populations, from species to ecosystem functions, and from isolated protected areas to integrated landscapes where humans and nature coexist (Tobias et al., 2025).

1.2. The Indo-Burma biodiversity hotspot and focus on Vietnam

This study focuses on Southeast Asia, particularly the Indo-Burma biodiversity hotspot, one of the biologically richest yet most severely threatened regions on the planet. Vietnam, located entirely within this hotspot, is a prime example of the tension between rapid economic development and natural resource conservation.

Vietnam ranks 16th in the world for biodiversity, with over 50,000 identified species, including thousands of endemic species found nowhere else. However, this richness is rapidly eroding. Recent reports indicate that 21% of mammals, 6.5% of birds, and 38% of freshwater fish species in Vietnam are threatened with extinction (WWF Vietnam, 2021). Habitat loss due to the conversion of forests to agricultural land (especially industrial crops like coffee, rubber, and acacia), combined with illegal hunting and wildlife trade, has pushed many species to the brink. The extinction of the Javan Rhinoceros in Vietnam in 2010 was a painful wake-up call regarding the failure of old conservation mechanisms against exploitation pressures (UNDP Viet Nam, 2018).

The Vietnamese government has demonstrated strong commitment through the enactment of the Law on Biodiversity (2008), the Law on Forestry (2017), and most recently, the National Biodiversity Strategy to 2030, Vision to 2050 (NBSAP) (Ministry of Natural Resources and Environment, 2022). However, a significant "implementation gap" exists between policy and practice, stemming from institutional barriers, a lack of sustainable financial resources, and limitations in scientific monitoring capacity (T. T. Pham et al., 2022).

1.3. Research objectives and questions

This report aims to synthesize and analyze the latest scientific evidence to provide a comprehensive view of integrated approaches in biological resource management. The goal is

not just to list problems but to identify transformative solutions capable of reversing biodiversity decline.

The core Research Questions (*RQs*) include:

RQ1: What strategies and theoretical frameworks are shaping the shift from single-species conservation to integrated ecosystem management in biodiversity hotspots?

RQ2: How is the Industry 4.0 technology revolution (eDNA, AI, Remote Sensing) changing the capacity for monitoring and managing biological resources?

RQ3: What are the specific challenges and barriers in implementing conservation policies in Vietnam, particularly institutional fragmentation and resource allocation?

RQ4: What role do local communities play in the integrated management model, and how do mechanisms like Co-management and Payment for Ecosystem Services (PES) truly deliver social and ecological effectiveness?

RQ5: What policy implications are necessary to realize the goals of NBSAP 2030 and the Global Biodiversity Framework?

2. METHODOLOGY AND THEORETICAL FRAMEWORK

2.1. Systematic Literature Review (SLR) process

This study applies the Systematic Literature Review (SLR) method based on the principles of the PRISMA statement (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to ensure transparency, objectivity, and reproducibility. The SLR process allows for the synthesis of fragmented evidence from various fields—from molecular biology and computer science to environmental economics and political science—into a unified analytical framework.

Search and Selection Strategy:

Literature searches were conducted on reputable academic databases (Scopus, Web of Science, Google Scholar) and grey literature repositories of international organizations (IUCN, UNDP, WWF, FAO, World Bank, GIZ, Vietnam government organizations). Search keywords were built around key thematic clusters:

Management themes: “integrated landscape management”, “ecosystem approach”, “biological resource management”, “nature-based solutions”.

Technology themes: “environmental DNA”, “eDNA”, “artificial intelligence in conservation”, “camera trapping”, “remote sensing”, “bioacoustics”.

Social/Policy themes: “community-based management”, “payment for ecosystem services”, “PFES”, “co-management”, “biodiversity governance”.

Geographic scope: “Vietnam”, “Southeast Asia”, “Indo-Burma hotspot”, “tropical ecosystems”.

Selection criteria included: *(1)* Documents published from 2015 to present (to ensure currency in technology and policy); *(2)* Documents written in English; *(3)* Studies with empirical data or specific policy analysis related to tropical or developing regions. Editorials without data, general textbooks, and studies prior to 2015 (except for original legal texts) were excluded.

2.2. Theoretical framework: From species to systems

This report is built upon the integration of three main theoretical frameworks:

1. Ecosystem approach: Adopted by the Convention on Biological Diversity (CBD), this is a strategy for the integrated management of land, water, and living resources that promotes conservation and sustainable use in an equitable way. This theory emphasizes that humans are an integral component of ecosystems, and management must consider impacts across multiple spatial and temporal scales (Triyanti et al., 2024).

2. Socio-Ecological Systems (SES): The SES framework views the interaction between biological factors (forests, species, water sources) and social factors (communities, markets, institutions) as a complex adaptive system. The sustainability of biological resources depends on the resilience of this entire system to external shocks such as climate change or market fluctuations (Dung et al., 2016; Dung et al., 2022; Mai & Kim, 2025).

3. Integrated Landscape Management (ILM): ILM is the practical application of the Ecosystem Approach in planning. It seeks to optimize diverse benefits (food, livelihoods, conservation) within the same landscape through coordination among multiple stakeholders. This framework helps resolve land-use conflicts—for example, between hydropower development and watershed protection—which are very common in Vietnam (Uetake et al., 2019).

3. "Beyond Species": Strategic shift in resource management

3.1. Limitations of species-focused conservation

While species-specific programs have achieved certain successes, they often face systemic limitations. First, protecting a single species does not guarantee safety for the entire ecosystem if foundational ecological processes are disrupted. For instance, protecting elephants without protecting their migration corridors leads to human-elephant conflict and genetic degradation due to population fragmentation (Tobias et al., 2025).

Second, species-focused strategies often overlook "non-charismatic" species that play critical ecological roles, such as fungi, insects, or soil microbes. Recent studies using hyperspectral remote sensing combined with soil eDNA have shown that microbial biodiversity correlates closely with vegetation health and forest resilience, yet this group is largely absent from traditional management plans (Skidmore et al., 2025).

The concept of "Beyond Species" proposes management based on ecosystem function. This means prioritizing the protection of "ecological networks"—such as pollination networks between plants and insects, or nutrient cycles maintained by scavengers (Tobias et al., 2025). Trophic pyramids and energy flow diagrams illustrate that ecosystem integrity depends on the diversity and abundance of organisms participating in these interactions, not just a checklist of present species.

3.2. Integrated Landscape Approach (ILM) in Southeast Asia

In Southeast Asia and Vietnam, ILM is gradually replacing sectoral management approaches. Instead of the Ministry of Agriculture managing crops, the Ministry of Natural Resources managing land, and Forest Rangers managing forests separately, ILM promotes interdisciplinary coordination across a shared landscape unit (e.g., river basin, coastal zone).

A prime example is initiatives in the Mekong Delta, where Nature-based Solutions (NbS) like mangrove restoration are integrated into planning for erosion control and climate change adaptation. This approach not only protects coastal biodiversity but also provides the critical ecosystem service of mitigating wave and storm impacts. However, ILM implementation faces significant difficulties due to administrative barriers. Land-use decisions are often made at the provincial level without inter-regional coordination, leading to the optimization of local

economic benefits (e.g., intensive shrimp farming) damaging the ecological function of the entire region (water pollution, mangrove loss) (Dang et al., 2021; Tun et al., 2025).

Furthermore, ILM requires private sector engagement. Large agricultural companies are beginning to realize that their supply chains depend on landscape health (water sources, soil fertility). Initiatives like "Production-Protection approaches" are being piloted, where companies commit to Zero Deforestation and support farmers in applying sustainable farming practices in buffer zones of protected areas (Denier et al., 2015).

4. THE TECHNOLOGICAL REVOLUTION IN BIODIVERSITY MONITORING

One of the most critical factors driving the "Beyond Species" approach is the emergence of advanced monitoring technologies. These tools help managers overcome the "taxonomic impediment" and collect data at unprecedented scale and precision.

4.1. Environmental DNA (eDNA): Seeing the invisible

Environmental DNA (eDNA) is considered a "game-changer" in biological monitoring. This technique allows for the detection of species presence via genetic material (skin cells, feces, mucus) left in the environment (water, soil, air) without direct observation or capture of animals (Leempoel et al., 2020).

Applications in Vietnam: In the Annamites (Truong Son range), one of the world's densest and most inaccessible forest regions, researchers have used eDNA collected from... terrestrial leeches (iDNA - invertebrate-derived DNA) to detect rare animals. Since leeches feed on the blood of various animals, analyzing DNA in their stomachs provides a comprehensive picture of the mammalian community in the area. This method has helped identify the presence of critically endangered and cryptic species like the Annamite striped rabbit and Saola, species that traditional camera trapping might miss or require immense effort to record (Drinkwater et al., 2021).

Comparison with camera trapping: Comparative research between soil eDNA and long-term camera trapping (9 years) shows that eDNA can detect all mammal species recorded by cameras, while also detecting many small mammals (rats, bats, insectivores) that cameras often miss. This proves eDNA is a powerful complementary tool, offering a more comprehensive view of biodiversity (Leempoel et al., 2020).

SuoiAI project: Recently, the "SuoiAI" project in Vietnam is pioneering the construction of a comprehensive dataset on aquatic invertebrates. By combining traditional sampling with machine learning image analysis, this project aims to automate the identification of bio-indicator species in streams, enabling rapid and large-scale assessment of water quality and ecosystem health. This is a prime example of using technology to monitor species groups often neglected ("Beyond Species" literally moving beyond large mammals) (Vo et al., 2025).

Challenges: However, widespread eDNA application in Vietnam faces a major barrier: the lack of reference libraries. To identify a species from an eDNA sample, a template gene sequence of that species must exist in the database for comparison. Given Vietnam's high biodiversity and many undescribed species, this library remains very incomplete (Leempoel et al., 2020). Additionally, hot and humid tropical conditions cause DNA to degrade quickly, requiring strict and costly sample preservation protocols.

4.2. Artificial Intelligence (AI) and monitoring automation

The explosion of data from camera traps, bioacoustics recorders, and satellites has created a new challenge: data overload. AI is solving this problem by automating processing and analysis.

Computer vision in camera trapping: Deep Learning models, particularly Convolutional Neural Networks (CNNs) like ResNet, YOLO, or MobileNet, are being trained to automatically recognize animal species in millions of camera trap images. Studies show these models can achieve over 90-99% accuracy in species classification, significantly reducing human time and effort (Song et al., 2025). In Vietnam, this technology is used not only for animals but is also being developed to identify precious timber species to control illegal logging.

Bioacoustic monitoring: AI is also applied to analyze forest audio recordings, helping detect calls of birds, gibbons, and even gunshots or chainsaws in real-time. This allows managers to react quickly to threats (Kerry et al., 2022).

Multi-source data integration: The modern trend is integrating AI with spatial data (GIS) and eDNA to create more accurate species distribution prediction models. For example, the eDITH (eDNA Integrating Transport and Hydrology) model combines hydrological data with eDNA to simulate the transport of genetic material in river basins, helping pinpoint exact locations of animal populations (Mas-Carrió et al., 2022).

4.3. Governance implications of technology

Technology is not just a technical tool but a governance tool. The transparency provided by eDNA and camera trap data can be used to evaluate the effectiveness of conservation interventions. For instance, quantitative camera trap data can prove whether forest patrol teams actually reduce hunting pressure, serving as a basis for results-based payment mechanisms (Microsoft and Planet, 2023).

5. PAYMENT FOR ECOSYSTEM SERVICES (PFES): ACHIEVEMENTS AND LIMITATIONS

Vietnam is a pioneer in Southeast Asia in legislating and implementing a national Payment for Forest Environmental Services (PFES) system through Decree 99/2010/ND-CP (Trædal & Vedeld, 2017). This is a crucial effort to shift from state budget-based management to sustainable market-based financial mechanisms.

5.1. Financial and social effectiveness

PFES has generated a massive and stable revenue stream for Vietnam's forestry sector. Revenue mainly comes from hydropower plants and clean water supply companies, entities that must pay forest owners to maintain water regulation and soil erosion control capabilities (Do et al., 2018).

Livelihood impact: In many localities, PFES money has become a significant income source for households contracted to protect forests, contributing from 16% to 74% of total household income in areas like Cat Tien National Park or Lam Dong (Pham et al., 2021). This has helped raise awareness about forest values and encouraged participation in patrol activities.

Social capital: Research indicates that PFES also contributes to strengthening community cohesion through joint patrol activities and village fund management (Roongtawanreongsri et al., 2023).

5.2. Limitations regarding biodiversity conservation effectiveness

Despite financial success, PFES in Vietnam faces major criticism regarding its actual effectiveness in biodiversity conservation ("Beyond Species").

Lack of additionality: A case study in Dak Lak province showed that after 8 years of PFES implementation, natural forest area continued to decline. The cause is that the payment level is too low (about 20-40 VND/kWh for hydropower) to compete with profits from converting forest land to high-value industrial crops like coffee, pepper, or durian (Do et al., 2018).

Distribution mechanism: The majority of PFES funds (about 90% in some cases) are paid to State Forest Management Boards, while only a small portion (about 10%) reaches communities and households directly protecting forests. This reduces people's motivation (Pham et al., 2021).

Misaligned objectives: Currently, PFES primarily pays based on *forest area* (vegetation cover) rather than *biodiversity quality*. A monoculture acacia forest (low biological value) can still receive environmental service payments equivalent to a species-rich natural forest, provided it meets coverage criteria. This does not incentivize the protection of animals or complex natural forest structures (Pham et al., 2021).

5.3. Towards PFES 2.0

For PFES to truly support biodiversity conservation, strong reform is needed: *Performance-based biodiversity payment:* Pilot models of additional payments for the presence of endangered species or habitat quality are needed, using data from camera traps and eDNA for verification (Microsoft and Planet, 2023). *Revenue diversification:* Expand PFES to other services such as carbon sequestration (C-PFES) and ecotourism to increase payment unit prices, creating sufficient economic incentive to prevent deforestation (Do et al., 2018).

6. Community-based governance and the role of citizens

The "Beyond Species" model cannot be separated from the human element. Local communities, especially ethnic minority groups living in and around protected areas, are the *de facto* managers of resources.

6.1. Community-BASED Forest Management (CBFM) model

Theory on CBFM posits that when communities are empowered with ownership and management of resources, they protect them more effectively than the state due to livelihood and cultural attachment.

Success at Xuan Nha: A pilot model at Xuan Nha Nature Reserve (Son La) demonstrated the effectiveness of combining traditional customary law with formal legal regulations to build village forest protection conventions. Success factors included clear objectives, stable rule systems, and strong support from local people (Phan & Nong, 2024).

General effectiveness: Literature reviews show that community-managed forests often have deforestation rates lower than or equivalent to strictly state-managed forests, but with lower costs and higher social benefits (Bayrak & Marafa, 2020; McElwee et al., 2022; Reyes et al., 2024).

6.2. Institutional and practical barriers

However, implementing CBFM in Vietnam faces many difficulties:

Lack of true ownership: In Vietnam's legal system, especially for Special-Use Forests (SUF), the community's role often stops at "contracted protection" rather than "co-management" with real decision-making power. Forest land allocated to communities is often poor, degraded, and of low economic value, reducing protection incentives (Agarwal et al., 2022).

Gender and social inequality: In many projects, the voices of women and marginalized groups are often drowned out by community elites (elite capture). Although women play a key role in collecting non-timber forest products and managing water, they are rarely involved in village forest management boards (Bayrak & Marafa, 2020; McElwee et al., 2022; Reyes et al., 2024).

Limitations in Marine Protected Areas (MPA): Although the 2017 Law on Fisheries recognized the concept of co-management in protecting aquatic resources, implementation in MPAs like Cu Lao Cham or Phu Quoc remains confused. Coordination mechanisms between MPA Management Boards (state) and fishing communities often lack legal binding and sustainable financial resources (Khuu et al., 2023; Pham et al., 2020; Quyet et al., 2023; Vo et al., 2020).

7. POLICY CHALLENGES AND IMPLEMENTATION GAPS IN VIETNAM

Vietnam has built a massive legal framework for conservation, but implementation effectiveness remains a big question mark.

Institutional fragmentation and conflict of interest: One of the biggest barriers is fragmentation in state management. Responsibility for biodiversity conservation is split between the Ministry of Natural Resources and Environment (MONRE) - responsible for biodiversity policy, and the Ministry of Agriculture and Rural Development (MARD) - responsible for managing the system of special-use forests and marine protected areas. Overlapping functions and lack of coordination between these two ministries often lead to confusion in direction and local implementation (Dung & Tuyet, 2025). Additionally, conflicts between economic development and conservation goals remain intense. Plans for hydropower, transport infrastructure, and tourism often encroach on ecologically sensitive areas. Environmental Impact Assessments (EIA) are often formalities and have not truly prevented projects harmful to biodiversity (WWF Vietnam, 2021).

"Empty forest" syndrome and law enforcement: Although Vietnam's forest cover has increased, forest quality and wildlife populations have declined. Rampant snaring ("snaring crisis") has turned many protected areas into "empty forests," where vegetation remains intact but large mammals and birds have been exterminated (Tilker et al., 2019). Law enforcement capacity remains weak, lacking personnel and equipment, while corruption has reduced the effectiveness of patrol and control work (Pham et al., 2022).

National strategy (NBSAP) and international commitments: The National Biodiversity Strategy to 2030 (NBSAP) sets ambitious goals such as expanding protected area coverage and restoring 20% of degraded ecosystems (Dung & Tuyet, 2025). To achieve this, Vietnam is considering recognizing "Other Effective Area-based Conservation Measures" (OECMs). OECMs present an opportunity to recognize informal conservation areas (such as sacred forests, community watershed forests, military zones) contributing to national conservation goals. However, there are currently no specific technical guidelines to identify and support OECMs (Do et al., 2024; Höffner et al., 2024).

A notable new policy proposal is the establishment of a "Natural Heritage Species" list alongside the endangered/rare species list. This effort aims to elevate the conservation status of endemic species with high cultural and ecological value, creating a stronger legal basis for prioritizing protection resources (Gray et al., 2025).

8. Discussion and implications: Towards the future

Integrating data into decision making: The Data Revolution needs to be translated into policy action. Data from eDNA and AI should not just reside in scientific papers but must be integrated into national biodiversity reporting systems. Building a centralized national database, standardizing eDNA sampling protocols, and sharing data between research and management agencies are urgent steps (Leempoel et al., 2020).

Restructuring conservation finance: The conservation finance model needs to shift from dependence on state budgets and international aid to blended finance mechanisms. Reforming PFES to pay for biodiversity outcomes, combined with carbon credit markets and green bonds, can generate breakthrough resources. However, equitable benefit-sharing mechanisms must be ensured so that local communities truly benefit and become active conservation partners (UNDP Viet Nam, 2018).

Substantive empowerment for communities: "Beyond Species" also means "Beyond Government." Conservation cannot succeed without the participation of civil society and communities. Co-management rights need to be institutionalized in the Law on Biodiversity and Law on Forestry, granting legal and financial power to community groups managing OECMs and buffer zones.

9. CONCLUSION AND RECOMMENDATIONS

This study confirms that the "Beyond Species" approach—integrating species management, ecosystem function, modern technology, and human communities—is the only path to secure a future for biodiversity hotspots like Vietnam. The shift from isolated conservation to integrated landscape management is happening but needs acceleration through institutional reforms and technology investment.

Based on the analysis, the report proposes the following recommendations:

Policy: Rapidly issue technical guidelines and legal frameworks for OECMs to expand conservation space beyond the formal special-use forest system. Promote substantive co-management mechanisms in National Parks and Marine Protected Areas.

Technology: Invest in building national DNA barcode reference libraries for Vietnamese flora and fauna to maximize the potential of eDNA technology. Apply AI and Digital Transformation in forest patrol and monitoring.

Finance: Reform PFES policy towards "multi-value," integrating payments for carbon sequestration and biodiversity conservation. Increase payment levels to ensure competitiveness with the opportunity costs of other land uses.

Governance: Enhance inter-ministerial coordination between MONRE and MARD through high-level coordination mechanisms or shared data integration. Improve law enforcement capacity to address snaring and illegal wildlife trade decisively.

Only by combining the power of technology, the wisdom of local communities, and the decisiveness of policy can we hope to reverse the extinction wave and preserve the priceless natural heritage for future generations.

List of Tables:

Table 1: Comparison of traditional and modern biodiversity monitoring methods

Feature	Traditional methods (Field surveys, manual camera trapping)	Modern methods (eDNA, AI, bioacoustics)
Target detection	Large mammals, easily observable birds. Hard to detect cryptic, small species.	All taxa (from microbes to large mammals), including cryptic, rare species (Leempoel et al., 2020).
Cost and time	Labor-intensive, long data processing time (manual image sorting).	High initial cost but decreases with scale. Fast processing via automation (Song et al., 2025).
Accuracy	Dependent on expert skill. Prone to misses.	High sensitivity, quantifiable. Dependent on reference libraries (Leempoel et al., 2020).
Environmental impact	Can be invasive (capture, disturbance).	Non-invasive (water/soil sampling), minimal impact on animals (Stephenson et al., 2022).
Applicability	Small scale, localized.	Large landscape scale, continuous real-time monitoring (T. Vo et al., 2025).

Table 2: Summary of barriers and solutions for biological resource management in Vietnam

Sector	Main barriers	Proposed solutions
Institutional	Fragmented management between MONRE and MARD; Functional overlap.	Inter-ministerial coordination mechanism; Unified national biodiversity data.
Financial	PFES does not pay for Biodiversity value; Low payment levels; Inequitable distribution.	PFES 2.0 (Carbon + Biodiversity integration); Green bonds; Community conservation funds.
Community	Lack of true land ownership; Low livelihood benefits; Gender inequality.	Institutionalize Co-management; Recognize community-managed OECMs; Empower women.
Technical	Lack of baseline data; "Empty forests" due to snaring; Weak monitoring capacity.	Apply eDNA/AI; Establish intelligent patrol systems (SMART); Strengthen law enforcement.

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ACHIEVING GENDER EQUALITY IN ENGINEERING: BARRIERS, IMPACTS, AND SOLUTION-FOCUSED STRATEGIES

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ABSTRACT

The field of engineering, a cornerstone of global innovation, remains a sector where gender inequality is widely experienced, despite housing a large number of talented female professionals. This study aims to comprehensively examine this issue, starting from the premise that achieving gender equality in the engineering profession is an ethical imperative and a critical strategic priority for the industry to realise its full potential. The study aims to provide a concrete and actionable roadmap for reversing inequality. In this paper, concrete indicators of gender inequality will be identified by comparing the representation rates of female engineers in employment, promotion, salary, and leadership positions from education to the highest levels of their careers with current data. In the second phase, structural, cultural, and psychological barriers (including social prejudices, a lack of role models, and difficulties with work-life balance) that hinder women's entry, retention, and advancement in this field will be analysed in depth. Finally, solution-oriented and actionable strategies will be developed in light of best practices and success stories from international literature. The paper's findings seek the source of inequality in engineering, not only in individual preferences but also in the barriers imposed by institutional and social structures. By clarifying existing inequality indicators, the potential negative impacts of the sector's lack of diversity on innovation and economic performance will be highlighted. Ultimately, this research lists actionable steps for educational institutions, the private sector, and policymakers to create fair and equal opportunities in the engineering profession. The study aims to trigger a comprehensive transformation in the engineering sector by encouraging the participation of female engineers and establishing inclusivity as a core value.

Keywords: Gender Equality in Engineering, Women Engineers, Diversity, Career Barriers

1. Introduction

The historical underrepresentation of women in STEM (Science, Technology, Engineering, and Mathematics) fields is a direct result of centuries-old cultural biases and systemic barriers. Due to social restrictions and institutional structures, women's contributions to these areas have been marginalised, which has limited the effective utilisation of potential human capital. Even pioneering figures like Marie Curie, who revolutionised radioactivity, and Ada Lovelace, who developed the first machine algorithm, often faced scepticism and limited recognition in their time (Gjersoe, 2018; Holman et al., 2018; Rubiano-Matulevich et al., 2019; Lee & Lee, 2025). While these successful individuals represent the exceptions of their time, ensuring gender diversity in STEM fields is a mandatory economic requirement in today's global economy to promote innovation, maximise productivity, and support sustainable economic growth. Diverse teams are better able to handle complicated challenges because they contribute a range of ideas and techniques, according to research (Jones et al., 2020).

The presence of women in the STEM fields, where innovation and adaptability are indispensable, brings in unique views that enhance collaboration. The presence of women in STEM fields also has a direct impact on the economy. A study conducted by the World Economic Forum indicated that if gender equality were realised in STEM fields, global GDP would be augmented by trillions of dollars, especially by reducing the labour shortage in the areas of high-demand technical professionals (Bell et al., 2011; Gómez-Zará et al., 2022). Taking care of this disparity is vital not only for the financial aspect but also for the social development and the prevention of negative technological externalities. Algorithms that are made with no diverse inputs, for instance, can cause market disruptions by unintentional bias reinforcement, such as unrecognised female faces in this case (Afreen et al., 2025; Ho et al., 2025). Thus, reaching gender diversity is not only an essential strategic economic necessity for equitable development, but it is also a pledge to capture human capital effectively and to redistribute that human capital through education, mentorship, and institutional reforms in a way that maximises social welfare. Yet the problem persists, and research into the barriers and the methods for promoting inclusivity has to be continuous. It is very important to understand the historical background, to shape the current debates and steer the future initiatives.

The paper aims to present the situation of women in STEM in terms of obstacles, progress, and possibilities. Even though significant policy changes, improved education, and positive social attitudes have occurred, the gender gap in these areas is still a major issue. This research tries to give a thorough insight into the core problems by looking at the different difficulties that women encounter, such as the institutional obstacles, the cultural biases, the psychological and personal factors, and so on (Galsanjigmed & Sekiguchi, 2023; Mashazi & Nkabinde-Thamae, 2025). The main purpose of writing this article is to point out the advancements in women's empowerment to join and do well in STEM (Science, Technology, Engineering, and Mathematics) careers. Through education reforms, mentorship programs, and international collaborations, gender disparities have been greatly reduced. Nevertheless, the article also highlights the unfair treatment that still exists, especially concerning the areas of leadership and access to the latest technological innovations. Furthermore, the paper outlines useful approaches to building an inclusive ecosystem.

The strategies include technology playing a role in connecting people, improving laws and regulations, and creating friendly places. In addition to the case studies and success stories that are presented, the study also includes examples of how both individuals and groups have worked together to change the environment for women in STEM positively (Alsaleh, 2024; Akanfe et al., 2025; Djatmiko et al., 2025). The aim of the paper is to motivate the different

parties—the researchers, the educators, the lawmakers, and the business leaders—to be more committed to gender parity in the future. It envisages a time when women will have the same chances as men to take part in and profit from the advancements in STEM, thus fostering global innovation and growth.

2. Literature Review

Due to social norms and gender prejudices, women have historically made important contributions to STEM disciplines but have often gone unrecognised. For instance, Ada Lovelace's work on Charles Babbage's Analytical Engine provided the groundwork for contemporary computing. Lovelace is sometimes considered to as the first computer programmer. Her understanding of algorithms extended beyond her period, demonstrating the ability of machines to carry out tasks other than mathematical computations (Zwolak, 2023). In a similar vein, Marie Curie was the first individual to receive two Nobel Prizes for her revolutionary work on radioactivity.

Rosalind Franklin, whose X-ray crystallography was crucial in understanding the double helix structure of DNA, is another prominent woman. Her achievements were overshadowed by those of her male coworkers, who received greater praise despite her crucial role (Franklin & Gosling, 1953; Crouse, 2007). NASA mathematician Katherine Johnson played a crucial role in determining the paths of space missions, including the Apollo 11 moon landing, but until recently, little was known about her. Rigid gender roles enforced by societal standards throughout these times frequently restricted women's access to professional and educational possibilities. Despite their propensity for science, many women were excluded from higher education or forced into administrative positions. Individuals who succeeded in making contributions to STEM were subjected to institutionalised prejudices, where their contributions were frequently disregarded or attributed to male colleagues (Loff, 2016; Jones et al., 2017). Instead of being discouraged by these difficulties, these pioneers cleared the path for later generations. Their tenacity emphasises the necessity of structural adjustments to acknowledge and encourage women's achievements in STEM fields while resolving prejudices that still exist today.

Technological developments and industrial revolutions have had a significant impact on the development of STEM professions, both creating new opportunities and redefining old ones. Mechanisation was brought about by the First Industrial Revolution, which greatly advanced industries like manufacturing and engineering. However, because cultural institutions restricted women to occupations outside of the industrial workforce, these improvements mainly excluded women (Khan et al., 2025)

With its emphasis on electricity and mass production, the Second Industrial Revolution started to make room for women in technical positions. For instance, women entered traditionally male-dominated engineering and manufacturing positions during World War II due to the demand for specialised labour. Although many of them returned to home responsibilities after the war, this was a turning point for women's involvement in STEM (Hirschman & Mogford, 2009; Wyrwich, 2019; Bikse et al., 2022). With the introduction of computing, information technology, and telecommunications, the 20th-century Digital Revolution drastically changed STEM professions. During this time, trailblazing women like Grace Hopper emerged, creating the first compiler and laying the groundwork for programming languages. The STEM environment has continued to be redefined by developments in biotechnology, nanotechnology, and artificial intelligence, opening doors in previously unthinkable disciplines (Kohnke & Zaugg, 2025; Song et al., 2025). Although women now have more opportunities thanks to technical advancements, cultural prejudice and structural restrictions still exist. Women are still

underrepresented in cutting-edge industries like artificial intelligence and quantum computing even today, underscoring the necessity of ongoing reform and campaigning to guarantee equal participation.

3. Gender Gaps Over Decades

Gender disparities in STEM continue despite advancements, which are a reflection of long-standing structural issues. The discrepancy in female involvement rates across STEM fields is seen in both historical and current data. For example, only 7% of American engineering graduates were female in the 1970s, compared to 58% in the life sciences (Charlesworth & Banaji, 2019). Although the number of women pursuing careers in biology and medicine had significantly increased by the 1990s, their representation in computer science and engineering remained below 20% (Verdín et al., 2018; Wang et al., 2023).

While there have been some improvements, recent data still shows gaps. Women accounted for 28% of the STEM workforce worldwide in 2020, with notable regional and discipline-specific differences. While women are nearly 50% more prevalent in the life sciences, they are still disproportionately underrepresented in computer science (around 25%) and engineering (less than 15%) (Meoli et al., 2024; EL-Deghaidy et al., 2025). Just 10% of top positions in STEM-related companies are held by women, demonstrating an even worse underrepresentation in leadership roles (George, 2024). There are a number of reasons why these gaps continue to exist. Girls are discouraged from pursuing STEM education due to societal biases, especially in mathematics and physics. Issues including gender pay disparities and a lack of mentorship opportunities play important roles in workplace environments that frequently lack the inclusion required to retain women (Helman et al., 2020; González-Gallego et al., 2025). Although they have shown potential, efforts to bridge these gaps—such as mentorship programs, diversity initiatives, and targeted scholarships—remain inadequate. In order to achieve gender parity in STEM, it is necessary to address underlying issues such as workplace practices, educational disparities, and cultural attitudes.

4. Obstacles that Women Encounter in STEM

The existing societal and cultural biases linked to women's roles in STEM have further led to the creation of gender stereotypes, which, in turn, adversely affect the entry of women into technical careers. Society has always been pretty clear from the start about the categories of careers that women are supposed to go to those characterised as nurturing or creative, while men are left with the choices of logical and technical fields. The survey conducted by Verdugo-Castro et al. (2023) points, among others, to such prevarications as the main reason that so few girls decide to pursue subjects with low popularity, such as mathematics and physics, especially in the countries of their origin. In addition, a global study encompassing 34 countries has admitted that girls living in places with a strong habit of gender stereotyping would have less ambitious plans concerning STEM jobs, even though their capabilities in these areas would be as good as or better than boys' (Ferreira et al., 2025).

The cultural reinforcement can sometimes be very delicate; for example, the parents’ and teachers’ unintentional actions could make girls refrain from entering technical careers, or the STEM fields could be presented as "male-dominated" ones. Moreover, the situation is made worse by the media. The women's presence in STEM fields is extremely limited, and mainly in the roles that are either supportive or secondary in the case of popular culture. The idea of "women non-belonging" in STEM is thus strengthened through these representations, which in turn corresponds to the development of women's still very low presence in technical occupations (Froehlich et al., 2022; Sikhosana et al., 2025). Cultural prejudices present extra challenges for women in STEM disciplines in the workplace, such as "double bind" scenarios

where they must strike a balance between conflicting expectations—being forceful enough to take the initiative but not so assertive that they are perceived as unlikable. These barriers not only hinder career advancement but also lead to higher turnover rates among women in technical fields (Ewim & Dosunmu, 2025). Initiatives to overcome these cultural barriers include mentorship programs and coding camps, which encourage young girls to explore STEM careers. Measures to legitimise the presence of women in technical professions are also crucial for dispelling stereotypes and fostering diversity (Martín-Peciña et al., 2025).

5. Barriers from Institutions

Women's advancement in STEM is still hampered by institutional impediments in academia and business. An uneven playing field is caused by structural problems such unequal compensation, few possibilities for career growth, and underrepresentation in leadership positions. According to a study by the American Association of University Women, women in STEM fields make about 20% less than men, even when they have the same credentials and occupations (Górska & Burlakova, 2025). In addition to depressing women, pay disparity indicates a lack of institutional commitment to gender equality.

Disparities in leadership are still another major problem. Despite making up nearly 50% of entry-level workers in several businesses, women hold less than 15% of leadership positions in STEM-related fields worldwide (Galsanjigmed & Sekiguchi, 2023). Biases in promotion procedures, a lack of mentorship opportunities, and the "glass ceiling" phenomenon that limits women's upward mobility are all factors contributing to this disparity. Other obstacles that women encounter in academia include fewer tenure-track jobs and restricted access to research funding. For instance, data indicate that female academics typically receive lower funds than their male counterparts, which restricts their capacity to carry out high-impact studies and obtain recognition (Correa et al., 2025). Additionally, women in STEM areas report greater rates of harassment at work, which raises turnover rates (Litzellachner et al., 2024).

To address these difficulties, institutional measures including fair hiring procedures, diversity training, and transparent pay audits are essential. Women can also overcome structural obstacles and advance in their careers by supporting leadership pipelines and mentorship programs (Corbett et al., 2024).

6. Psychological and Personal Obstacles

Women's experiences and retention in STEM professions are greatly impacted by psychological and personal obstacles such as impostor syndrome and a lack of role models. Women in STEM fields are disproportionately affected by impostor syndrome, which is characterised by feelings of inadequacy and self-doubt despite obvious accomplishments. According to studies, imposter syndrome has affected up to 70% of women in STEM at some time in their careers (Clark et al., 2021).

The information discussed above is often the consequence of working in male-dominated areas, which puts extra pressure on women to prove their worth. The situation gets even more complicated because there are very few visible role models in the STEM field. It is very difficult for lots of women to envision a successful career in technical fields when they cannot find mentors or leaders who have gone through similar situations. A particular research found that girls who have female role models in science and engineering are more inclined to choose STEM careers; however, that exposure is quite limited (González-Pérez et al., 2020; Mansour, 2025). Such mental issues also lead to diminished confidence when it comes to applying for high-stakes projects or taking up leadership positions. It has been found that women only apply for jobs if they meet 100% of the requirements, while men do so even with only 60%

(Fluchtmann et al., 2021). This reluctance on the part of women often leads to their not being considered for promotion opportunities. In order to get through these barriers, it is extremely important to set up support networks and provide women in STEM with mentorship opportunities. Some of the initiatives that are aimed at reducing the impact of impostor syndrome are leadership development, peer groups, and sponsorship programs. Moreover, the presence of women in the STEM fields can be enhanced through conferences, the media, and educational settings, which in turn will grow the self-esteem and encourage the upcoming generation of women to go for it and be the best in these fields (Lee et al., 2024).

7. Ongoing Projects and Efforts

The goal of initiatives to boost women's involvement in STEM education has been to remove obstacles that deter females from pursuing technical fields. Young women's curiosity and self-assurance have been greatly boosted by scholarships, focused programs, and neighbourhood projects. Girls are encouraged to pursue further education in STEM fields by scholarship schemes. Thousands of women around the world have benefited from programs like the L'Oréal-UNESCO For Women in Science Fellowship, which offer financial support and acknowledgement for their contributions to scientific research (Freedman et al., 2023). In a similar vein, regional awards like the Google Anita Borg Memorial Scholarship are designed to bridge the gender gap in technological areas by empowering women in computer science (George, 2024).

Programs for younger girls have just as much of an impact. Girls are introduced to programming, robotics, and business through groups like Girls Who Code and Technovation, which also offer mentorship and practical experience. By addressing the gender gap at a young age, these programs help dispel social preconceptions and develop fundamental skills (Torres-Ramos et al., 2021). As an illustration of the long-term benefits of early intervention, participants in these programs have gone on to win international coding competitions and land internships in prestigious software businesses. Additionally, attempts to include gender-sensitive teaching methods into STEM curricula have gained momentum (Nikghadam-Hojjati et al., 2025). To guarantee a nurturing environment for young students, teacher training initiatives that encourage inclusivity and eradicate gender prejudices are also being implemented globally. In order to ensure that young women see STEM as an accessible and fulfilling professional option, these educational changes must be able to provide them with tools, mentorship, and role models (Bustamante-Mora et al., 2025).

The topic has gained international attention thanks to global initiatives and legislation that support gender equality in STEM, which have also created platforms for cooperation and innovation. Progress has been fueled in large part by regional initiatives in poor nations and organisations like UN Women. Campaigns by UN Women, like Step It Up for Gender Equality in STEM, promote collaborations and legislative changes that support women's involvement in STEM. These efforts highlight the role of institutions and governments in establishing supportive frameworks, such as fair pay, anti-discrimination laws, and access to high-quality education (Lwamba et al., 2022).

Additionally, regional initiatives have made a substantial contribution. Through summer camps, scholarships, and mentoring by female scientists, the Vigyan Jyoti initiative in India encourages high school girls to pursue professions in STEM. Girls' enrollment in STEM programs at prestigious universities has significantly increased since the program's inception (Mehta et al., 2024). In a similar vein, the African Girls Can Code Initiative in Africa prepares young women for jobs in technology and engineering by providing them with digital and technical skills (Awuah et al., 2025).

In industrialised nations, policy frameworks have also been crucial. For example, the Gender Equality Strategy of the European Union uses funding, research grants, and public awareness initiatives to raise the number of women in STEM disciplines. In order to ensure inclusivity in ground-breaking studies, programs such as Horizon Europe offer special financing possibilities for female researchers (Irod et al., 2025). Problems like resource inequality and cultural prejudices still exist in spite of these initiatives. Achieving long-term impact requires bolstering international partnerships and guaranteeing ongoing funding for these projects. This chart highlights the collective efforts for gender equality in STEM by giving a summary of significant international initiatives and their quantifiable results (Işıkgöz et al., 2025).

8. Contributions and Success Stories

Pioneering women have made significant contributions to STEM throughout history, frequently going against social norms to produce ground-breaking discoveries. In addition to advancing scientific knowledge, their accomplishments have opened doors for upcoming generations of women working in technical domains. Ada Lovelace, one of the pioneers, is credited with being the first person to program a computer. The concept of algorithms was first introduced by her work on Charles Babbage's Analytical Engine, which showed that machines were capable of doing more than just basic calculations (Zwolak, 2023). Lovelace's vision established the groundwork for contemporary computers, an industry that still influences society today.

Two-time Nobel laureate Marie Curie transformed the study of radioactivity. In addition to advancing science, her discoveries of radium and polonium had a significant impact on medicine, resulting in the creation of radiation therapy for the treatment of cancer (Shanbhag et al., 2024). Despite working in a setting where men predominated, Curie's accomplishments made her a symbol of excellence and tenacity. Rosalind Franklin was instrumental in the discovery of DNA's structure in the middle of the 20th century. Although her efforts were overshadowed by those of her male peers, her X-ray crystallography study provided the crucial data required to identify the double-helix structure (Freedman et al., 2023). NASA mathematician Katherine Johnson played a crucial role in determining the Apollo missions' paths, guaranteeing the accomplishment of space exploration projects (Johnson, 2020).

These trailblazers serve as examples of the tenacity and intelligence of women in STEM, motivating continued efforts to honour and celebrate their accomplishments. Society may continue to combat prejudices and advance inclusivity in scientific fields by recognising their accomplishments (García-Silva et al., 2025).

Modern women in STEM are spearheading innovative initiatives that tackle some of the most important global issues. Their work demonstrates the revolutionary influence of female leadership in science and technology across a wide range of industries, from renewable energy to artificial intelligence. Renowned computer scientist and AI researcher Fei-Fei Li has led the way in the advancement of artificial intelligence. Her leadership at Stanford University's Human-Centred AI Institute and her work on computer vision provide a strong emphasis on ethical AI development, making sure that advances in technology benefit people (Etchemendy & Li, 2024).

Li's efforts have impacted accessibility, education, and healthcare uses of AI. Katharine Hayhoe is a prominent climate scientist and campaigner in the field of environmental research. Her outreach initiatives have assisted in bridging the knowledge gap between scientists and the general population, and her research on the effects of climate change has influenced international policy (Geiger et al., 2022). The groundbreaking gene-editing technique CRISPR-

Cas9 was co-developed by Dr Jennifer Doudna, another renowned inventor. This discovery has revolutionised genetics, allowing for more precise DNA changes and creating new opportunities in agriculture and health (Gostimskaya, 2022). Doudna has won a Nobel Prize and gained international prominence for her contributions to the advancement of biotechnology. These contemporary innovators inspire the next generation to seek careers in science and technology by demonstrating the potential of women in STEM to bring about significant change.

Conclusion

The various obstacles, advancements, and potential directions for attaining gender inclusion in STEM professions have all been discussed in this article. Women have historically made substantial contributions to STEM, but their presence and success have been constrained by widespread institutional, societal, and personal obstacles. Girls are discouraged from pursuing STEM occupations at a young age due to societal biases and gender stereotypes, and institutional obstacles such as unequal compensation, a lack of leadership chances, and insufficient mentorship further impede women's advancement. Another level of complication is added by personal issues like impostor syndrome and a lack of role models. However, a number of projects aiming at closing these disparities demonstrate improvement. Young women are now more emboldened to pursue STEM education thanks to educational innovations like coding programs and grants.

Mentorship programs and flexible work schedules are two examples of industry initiatives that have improved career advancement and retention. Women now have more access to technology and resources thanks to international initiatives like UN Women's campaigns and regional initiatives in underprivileged areas (Lwamba et al., 2022). Women now have more opportunities to lead and innovate in STEM domains, such as artificial intelligence, quantum computing, and green technology. The STEM ecosystem may become more inclusive by implementing proactive tactics, including legislation changes, community development initiatives, and institutional accountability, guaranteeing that women are not just participants but also leaders in influencing the future. We may imagine a route toward a diverse and equitable STEM landscape that benefits individuals, corporations, and societies equally by tackling systemic impediments and building on recent advancements. Beyond personal success, gender inclusion promotes advancement in society. It gives communities more power, motivates the next generation, and produces role models who dispel misconceptions. Women's achievements in STEM professions have already started to change cultural perceptions, inspiring young girls to pursue careers in traditionally male-dominated fields. It will take consistent work, cooperation, and dedication from all parties involved to achieve gender parity in STEM (Dickson & Alharthi, 2025). We can build inclusive ecosystems and remove structural barriers to ensure that chances in science and technology are not determined by a person's gender in the future.

This change will guarantee that STEM areas continue to develop, innovate, and address the urgent problems of our day in addition to creating a more equitable world. A vibrant, just, and creative global community is built on inclusivity, which is more than just a goal.

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TARİHİ YAPILARIN DİJİTAL KORUNMASINDA YENİ PARADİGMA: YAPAY ZEKÂ DESTEKLİ BELGELEME, KÜLTÜREL İLETİŞİM VE SÜRDÜRÜLEBİLİR TURİZM MARKALAŞMASI

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ÖZET

Bu çalışma, tarihi yapıların korunmasında dijital teknolojilerin rolünü mimarlık, iletişim ve pazarlama disiplinlerinin kesişiminde ele almaktadır. Günümüzde kültürel miras yapıları yalnızca fiziksel olarak korunmakla kalmamakta; aynı zamanda dijital ortamda belgelenmekte, temsil edilmekte ve sürdürülebilir turizm stratejilerinin merkezinde yeniden konumlandırılmaktadır. Mimarlık açısından çalışma, yapay zekâ destekli 3B tarama, fotogrametri ve BIM tabanlı belgeleme tekniklerinin tarihi yapıların özgün niteliklerini koruma süreçlerine katkısını tartışmaktadır. İletişim perspektifinde, dijital arşivler, artırılmış gerçeklik uygulamaları ve kültürel hikâye anlatımı yöntemlerinin mirasın görünürlüğünü ve toplumsal farkındalığı nasıl artırdığı incelenmektedir. İşletme ve marketing boyutunda ise, tarihi yapıların dijital temsilinin sürdürülebilir turizm markalaşmasına etkisi, destinasyon imajı ve ziyaretçi deneyimi açısından değerlendirilmektedir Sonuç olarak çalışma, dijital koruma teknolojilerinin yalnızca teknik bir süreç olmadığını; kültürel iletişim ve turizm ekonomisiyle bütünleşen çok katmanlı bir dönüşüm olduğunu ortaya koymaktadır.

Anahtar Kelimeler: Dijital Koruma, Kültürel Miras, Yapay Zekâ, AR/VR, Turizm Markalaşması

A NEW PARADIGM IN DIGITAL PRESERVATION OF HISTORIC STRUCTURES: AI-BASED DOCUMENTATION, CULTURAL COMMUNICATION, AND SUSTAINABLE TOURISM BRANDING

ABSTRACT

This study examines the role of digital technologies in the preservation of historic structures through the integrated perspectives of architecture, communication, and marketing. Today, cultural heritage buildings are not only physically conserved but also digitally documented, represented, and repositioned at the center of sustainable tourism strategies. Architecturally, the research discusses how AI-assisted 3D scanning, photogrammetry, and BIM-based documentation contribute to safeguarding the authenticity of historic structures. From a communication standpoint, it analyzes how digital archives, augmented reality applications, and cultural storytelling enhance the visibility and public understanding of heritage assets. In the marketing domain, the study evaluates how the digital representation of historic buildings shapes sustainable tourism branding, destination image, and visitor experience. The paper concludes that digital preservation technologies constitute not merely a technical process but a multilayered transformation intertwined with cultural communication and tourism economics.

Keywords: Digital Preservation, Cultural Heritage, Artificial Intelligence, AR/VR, Tourism Branding

Giriş

Dijital dönüşüm, kültürel miras alanlarında köklü bir paradigma değişimini beraberinde getirmiş; tarihi yapıların korunması, belgelenmesi ve aktarılması süreçleri geleneksel yöntemlerin ötesine geçerek yapay zekâ, 3B modelleme, dijital ikiz teknolojileri ve artırılmış gerçeklik (AR/VR) uygulamalarıyla yeniden tanımlanmıştır (Pocobelli et al., 2018). Tarihi yapıların korunması artık yalnızca fiziksel müdahalelerle sürdürülen bir mimari pratik olmaktan çıkmış; dijital kültürel iletişim, veri temelli belgeleme ve turizm odaklı markalaşma stratejilerini kapsayan çok disiplinli bir alana dönüşmüştür. Günümüzde UNESCO, ICOMOS ve uluslararası araştırma ağları; dijital koruma teknolojilerinin sürdürülebilir kültürel miras yönetiminde kritik bir rol üstlendiğini vurgulamaktadır (UNESCO, 2022). Dijital ikiz sistemleri, yapay zekâ destekli hasar tespit yazılımları, AR destekli deneyim alanları ve dijital arşivleme yöntemleri, hem mimari koruma süreçlerini güçlendirmekte hem de kültürel mirasın toplumsal görünürlüğünü artırarak turizm ekonomisine yeni değerler kazandırmaktadır. Bu çalışma, yapay zekâ destekli dijital belgelemenin teknik boyutlarını, kültürel iletişim stratejileriyle birleşen dijital hikâyeleştirme yöntemlerini ve bunların sürdürülebilir turizm markalaşmasına etkisini bütüncül bir çerçevede ele almaktadır.

1. Kavramsal Çerçeve

1.1. Dijital Kültürel Miras ve Yeni Koruma Yaklaşımı

Dijital kültürel miras, tarihi yapıların dijital araçlar üzerinden belgelenmesi, korunması ve erişilebilir hâle getirilmesini kapsayan yeni bir kavramsal yapıdır. Fotogrametri, lazer tarama, 3B rekonstrüksiyon, dijital arşivleme ve sanal mekân oluşturma gibi yöntemler kültürel mirasın hem fiziksel hem dijital ortamda sürdürülebilir şekilde yaşatılmasını mümkün kılmaktadır (Almeida & Ferreira, 2021).

Bu yaklaşım üç temel dönüşüm üretmektedir:

- **Teknik dönüşüm:** Yüksek doğruluklu 3B modeller, veri temelli hasar analizi, dijital ikiz üretimi.
- **Toplumsal dönüşüm:** Mirasın daha geniş kitlelerce erişilebilir ve anlaşılır hâle gelmesi.
- **Ekonomik dönüşüm:** Dijitalleştirilmiş mirasın yeni deneyim formatlarıyla turizm değerine dönüşmesi.

1.2. Yapay Zekâ Destekli Mimari Belgeleme

Yapay zekâ, kültürel miras belgeleme süreçlerinde yeniden yapılandırmayı hızlandıran ve doğruluk oranını artıran bir teknoloji olarak öne çıkmaktadır.

AI tabanlı uygulamalar:

- Yüzey bozulmalarını ve çatlakları otomatik sınıflandırır,
- Fotogrametrik verileri derin öğrenme ile işler,
- Eksik tarihi öğeleri tahmini modellerle tamamlar,
- Lazer tarama verilerinden saniyeler içinde 3B model çıkarır,
- Restorasyon için dijital karar destek sistemi sunar (Giusti & Calantropio, 2020).

Bu süreç, kültürel miras korumasında **hız, doğruluk ve maliyet avantajı** sağlayarak restorasyonun planlama aşamalarını kökten değiştirmektedir.

1.3. Dijital Kültürel İletişim ve Turizm Markalaşması

Tarihi yapılar yalnızca belgelenmekle kalmaz; dijital iletişim stratejileri sayesinde hikâye anlatımı yoluyla yeniden anlam kazanır. AR/VR deneyimleri, sanal müzeler, dijital turlar, mobil uygulamalar ve sosyal medya içerik stratejileri, kültürel mirası yeni kuşaklara aktarmada güçlü araçlar hâline gelmiştir (Pescarin, 2018).

Bu yaklaşım turizm alanında üç temel etki yaratır:

1. **Destinasyon Kimliği:** Dijital deneyim, tarihi yapıyı markasal bir değer unsuruna dönüştürür.

2. **Ziyaretçi Deneyimi:** Dijital rehberlik, interaktif hikâyeler ve sanal keşifler ziyaretçinin mekânla duygusal bağını artırır.

3. **Sürdürülebilirlik:** Fiziksel aşınma riskini azaltır, turizmin mekân üzerindeki baskısını düşürür.

Dijital temsil, tarihi yapıyı küresel görünürlüğe taşıyarak turizm markalaşmasını destekleyen stratejik bir araç hâline gelir (Yung & Chan, 2022).

2. Yöntem

Bu araştırma, nitel araştırma yöntemlerinden literatür taraması, kavramsal analiz ve disiplinler arası karşılaştırmalı inceleme tekniklerine dayanmaktadır.

Tarama sürecinde:

- Mimarlık: Dijital belgeleme ve yapay zekâ tabanlı koruma yöntemleri
- İletişim: Dijital kültür, AR/VR iletişimi, hikâyeleştirme stratejileri
- İşletme/Marketing: Turizm markalaşması, destinasyon imajı, dijital deneyim pazarlaması

alanlarında 2018–2024 yılları arasında yayımlanan uluslararası makaleler incelenmiştir.

Veriler Web of Science, Scopus, SpringerLink ve Google Scholar üzerinden toplanmış; bulgular konu başlıklarına göre tematik analizle sınıflandırılmıştır.

3. Bulgular

3.1. Yapay Zekâ Destekli Belgelemede Paradigma Değişimi

Araştırma bulguları, yapay zekâ tabanlı dijital belgeleme tekniklerinin kültürel miras koruma alanında devrim niteliğinde bir dönüşüm yarattığını göstermektedir. Geleneksel yöntemler; insan gözüne dayalı gözlem, manuel çizim, sınırlı hassasiyete sahip fotogrametik ölçümler veya uzun süren CAD tabanlı modelleme süreçleri gibi aşamalar içerirken, yapay zekâ destekli modeller hem zamansal hem ekonomik hem de teknik açıdan çok daha üstün performans sergilemektedir.

Derin öğrenme algoritmaları, fotogrametri ve lazer tarama çıktılarındaki milyonlarca veri noktasını saniyeler içerisinde işleyebilmekte; yüksek çözünürlüklü 3B dijital ikiz modeller üreterek yapıların özgün detaylarını birebir yansıtabilmektedir (Giusti & Calantropio, 2020). Bu sayede:

- **Hasar tespiti otomatikleşmiş**, çatlaklar, nem lekeleri, deformasyonlar ve malzeme kayıpları AI tarafından birkaç saniyede sınıflandırılabilir hâle gelmiştir.

- **Eksik veya tahrip olmuş mimari öğeler** (süsleme parçaları, kabartmalar, taş detayları) dijital rekonstrüksiyon modelleriyle gerçekçi şekilde yeniden üretilebilmekte; böylece restorasyon projelerine bilimsel doğruluk katılmaktadır.
- **3B dijital çıktılardaki hata payı düşmekte**, yapay zekâ yüzey gürültülerini temizlemekte ve veriyi tutarlı hâle getirmektedir.
- **Karar destek sistemleri**, restorasyon ekiplerine alternatif müdahale senaryoları sunmakta; malzeme uyumu, statik risk analizi ve bozulma olasılıkları gibi teknik değerlendirmeler otomatik olarak yapılabilmektedir.
- **Uzun vadeli izleme** (digital monitoring) mümkün olarak yapının yıllar içerisindeki bozulma seyri dijital ortamda karşılaştırılabilmektedir.

Bu tümleşik süreç, dijital belgelemenin yalnızca restorasyon projeleri için bir "yardımcı araç" olmaktan çıktığını; kültürel miras yönetiminin merkezine yerleşen zorunlu bir metodolojik bileşene dönüştüğünü göstermektedir. Böylece yapıların hem korunabilirliği hem de gelecek kuşaklara aktarılabilirliği daha sürdürülebilir bir zemine oturmaktadır.

3.2. Dijital Kültürel İletişimde Görünürlük Artışı

Bulgular, dijital kültürel iletişimin miras alanlarının toplumsal bilinirliğini ve kültürel değerini artırmada kritik bir rol oynadığını göstermektedir. Özellikle AR/VR teknolojileri sayesinde ziyaretçiler, tarihi yapıların özgün hâllerini, farklı dönemlerdeki değişimlerini veya günümüzde kaybolmuş bölümlerini **etkileşimli bir deneyim** olarak keşfedebilmektedir (Reilly, 2020).

Bu dönüşüm üç temel görünürlük biçimi sağlamaktadır:

1. **Erişilebilirlik Temelli Görünürlük:**
Dijital turlar ve 3B sanal müzeler, coğrafi veya fiziksel erişim engellerini ortadan kaldırarak kültürel mirasa herkesin erişmesini sağlamaktadır. Bu durum özellikle eğitim kurumları, engelli bireyler, yurtdışı izleyiciler ve genç kuşaklar için büyük avantaj yaratmaktadır.

2. **Duygusal Görünürlük:**
Dijital hikâyeleştirme teknikleri (narrative-based visualization), ziyaretçilerin mekânla duygusal bağ kurmasını kolaylaştırmakta; yapının tarihsel kimliği dramatik, sanatsal veya tematik anlatılarla güçlendirilmektedir. Böylece kültürel miras “izlenen” bir olgu olmaktan çıkarak “deneyimlenen bir kültürel persona”ya dönüşmektedir.

3. **Kültürel Bellekte Kalıcılık:**
Sosyal medya temelli paylaşımlar, kısa videolar, podcastler ve mobil uygulamalar aracılığıyla miras değerleri yaygınlaşmakta; özellikle genç kuşakların tarihe yönelik ilgisi artmaktadır. Dijital içerikler, mirasın kolektif bellekte daha güçlü yer edinmesini sağlamaktadır.

Sonuç olarak dijital iletişim, kültürel mirası yalnızca teknik olarak belgelemekle kalmaz; ona yeni bir **kültürel yaşam alanı** kazandırır. Dijital ortamda temsil edilen miras, fizikselin ötesine geçerek kültürel bir içerik ürünü hâline gelir.

3.3. Sürdürülebilir Turizm Markalaşmasında Dijital Temsilin Rolü

Bulgular, dijital temsilin sürdürülebilir turizm markalaşmasında çok yönlü ve stratejik bir güç olduğunu ortaya koymaktadır. Dijitalleştirilmiş tarihi yapılar, destinasyonların modern, yenilikçi ve teknolojiyle uyumlu bir kimlik kazandığını göstererek “çağdaş destinasyon” algısını güçlendirmekte; bu durum turistlerin bölgeye karşı ilk izlenimini olumlu yönde etkilemektedir. Dijital deneyim yaşayan ziyaretçilerin fiziksel ziyarete daha yüksek

motivasyon duyduğu görülmekte; AR/VR destekli dijital ön-izleme deneyimleri, özellikle uluslararası turistlerde mekâna karşı merak ve bağlılık oluşturmaktadır. Ayrıca dijitalleştirilmiş kültürel miras, farklı yaş grupları ve farklı kültürel geçmişlerden gelen kullanıcılar için erişilebilir bir öğrenme ve keşif ortamı yaratmakta; böylece ziyaretçi yelpazesi genişlemektedir. Dijital içeriklerin sürekli güncellenmesi, etkileşimli haritalar, sanal sergiler, kısa hikâye videoları, tematik dijital turlar ve kullanıcı katılımına açık dijital platformlar, destinasyonla kurulan bağı güçlendirmekte ve ziyaretçi sadakatini artırmaktadır. Bununla birlikte dijital temsil, fiziksel ziyaret yoğunluğunun kontrol edilmesine de katkı sağlayarak sürdürülebilir turizmin önemli bir gerekliliği olan "mekânsal taşıma kapasitesinin" korunmasına imkân sunmaktadır. Yoğun ziyaretçi trafiğine sahip hassas kültürel miras alanlarında fiziksel yükün azaltılması, dijital ikiz modeller, sanal turlar ve uzaktan erişilebilir kültürel deneyimlerle mümkün olmakta; bu süreç, hem koruma politikalarına hem de destinasyon yönetimine önemli bir destek sağlamaktadır. Tüm bu bulgular, dijital temsilin yalnızca kültürel mirası görünür kılmakla kalmadığını; aynı zamanda ekonomik, kültürel ve çevresel sürdürülebilirliği güçlendiren bütünsel bir turizm markalaşma aracı hâline geldiğini göstermektedir.

Sonuç

Bu çalışma, dijital dönüşüm çağında tarihi yapıların korunması, belgelenmesi ve yeniden anlamlandırılması süreçlerinin yalnızca teknik bir müdahale alanı olmaktan çıkarak mimarlık, yapay zekâ teknolojileri, kültürel iletişim ve turizm markalaşması disiplinlerinin kesişiminde gelişen çok katmanlı bir yapıya dönüştüğünü ortaya koymuştur. Elde edilen bulgular, yapay zekâ destekli belgeleme yöntemlerinin kültürel miras alanlarında geleneksel koruma pratiklerinin yerini önemli ölçüde aldığına ve bu teknolojilerin tarihsel veriyi hem daha doğru hem daha hızlı hem de daha sürdürülebilir biçimde işleyerek yeni bir koruma paradigması oluşturduğuna işaret etmektedir. Derin öğrenme algoritmaları, 3B dijital ikiz modelleri ve otomatik hasar tespit sistemleri, restorasyon süreçlerinde karar vericilere yüksek doğruluklu veri sağlayarak kültürel mirasın geleceğe aktarılmasında kritik bir rol oynamaktadır.

Dijital kültürel iletişim boyutu incelendiğinde, dijital hikâyeleştirme yöntemlerinin (AR/VR deneyimleri, etkileşimli dijital arşivler, sanal turlar ve sosyal medya temelli içerik stratejileri) tarihi yapıların toplumsal görünürlüğünü artırdığı ve kültürel mirasın yalnızca belgelenen bir obje değil, yeniden üretilen ve deneyimlenen bir kültürel anlatı unsuru hâline geldiği görülmektedir. Dijital temsiller, özellikle genç kuşakların kültürel mirasa yönelik farkındalığını artırmakta; mekânın tarihsel, estetik ve sembolik boyutlarını daha erişilebilir ve daha etkileşimli hâle getirerek kültürel belleği güçlendirmektedir. Böylece kültürel miras, dijital ortamda yeni bir yaşam alanı kazanmakta; mekânsal kimliğin çok daha geniş bir izleyici kitlesiyle paylaşılmasına olanak sağlamaktadır.

Turizm ve pazarlama perspektifinden bakıldığında, dijital temsilin destinasyon imajı üzerinde belirleyici bir etkiye sahip olduğu ve dijitalleştirilmiş kültürel miras unsurlarının sürdürülebilir turizm markalaşmasını desteklediği ortaya çıkmıştır. Dijital içerikler, ziyaretçi motivasyonunu artırmakta; yenilikçi dijital deneyimler destinasyonların rekabet gücünü yükseltmekte; dijital ikiz modeller ve sanal sergiler fiziksel ziyaret baskısını azaltarak sürdürülebilir turizm politikalarına katkıda bulunmaktadır. Dijitalleşme sayesinde kültürel miras, küresel ölçekte görünürlük kazanmakta; destinasyon sadakati, dijital anlatılar ve etkileşimli deneyimlerle güçlenmektedir.

Genel olarak, bu çalışma dijital koruma teknolojilerinin yalnızca mimari bir belgeleme aracı değil; kültürel iletişim, eğitim, turizm ekonomisi, destinasyon yönetimi ve toplumsal farkındalık üretimi açısından bütüncül bir dönüşüm mekanizması olduğunu göstermiştir. Yapay

zekâ tabanlı belgeleme, dijital iletişim yöntemleri ve sürdürülebilir turizm stratejilerinin entegrasyonu, tarihi yapıların hem korunabilirliğini hem erişilebilirliğini hem de ekonomik ve kültürel değerini artıran yeni bir paradigma ortaya koymaktadır.

Bu bağlamda geleceğin kültürel miras politikalarının:

- yapay zekâ destekli dijital ikiz sistemlerine,
- sürdürülebilir turizm odaklı dijital markalaşma stratejilerine,
- kültürel hikâyeleştirmeyi merkeze alan iletişim yaklaşımlarına,
- erişilebilir ve katılımcı dijital miras modellerine

dayanması gerekmektedir.

Tüm bulgular, dijital korumanın gelecek kuşaklara aktarılacak kültürel mirasın niteliğini artıran, yenilikçi, kapsayıcı ve sürdürülebilir bir yol haritası sunduğunu göstermektedir.

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RİSK ALTINDAKİ TARİHİ YAPILARIN KORUNMASINDA VERİ ANALİTİĞİ, TOPLUMSAL İLETİŞİM VE KORUMA EKONOMİSİ ÜZERİNE ÇOKDİSİPLİNLİ BİR YAKLAŞIM

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ÖZET

Bu çalışma, deprem, iklim değişikliği ve çevresel riskler nedeniyle tehdit altındaki tarihi yapıların korunmasında veri analitiği, iletişim stratejileri ve koruma ekonomisinin birlikte nasıl kullanılabileceğini incelemektedir. Mimarlık ve mühendislik açısından, sensör tabanlı yapısal sağlık izleme (SHM), titreşim ölçümleri, nem/ısı analizleri ve dijital ikiz (digital twin) modellerinin risk tespiti ve müdahale kararlarına sağladığı katkı ele alınmaktadır. İletişim boyutunda, yerel halkın bilgilendirilmesi, kriz iletişimi, sosyal medya farkındalık kampanyaları ve kültürel değer anlatılarının koruma başarısına etkisi analiz edilmektedir. İşletme/marketing perspektifinde ise, tarihi yapıların restorasyon finansmanı, sponsor bulma stratejileri, kültür ekonomisi ve koruma projelerinin marka değerine dönüşme potansiyeli tartışılmaktadır. Sonuç olarak çalışma, tarihi yapıların korunmasını teknik bir mühendislik süreci olmaktan çıkarıp; veri yönlendirmeli, toplumsal katılımlı ve ekonomik olarak sürdürülebilir çok katmanlı bir yönetim modeli olarak yeniden tanımlamaktadır.

Anahtar Kelimeler: Yapısal Sağlık İzleme, Tarihi Yapılar, Koruma Ekonomisi, Dijital İkiz, Kriz İletişimi

A MULTIDISCIPLINARY APPROACH TO PROTECTING AT-RISK HISTORIC STRUCTURES: DATA ANALYTICS, PUBLIC COMMUNICATION, AND CONSERVATION ECONOMICS

ABSTRACT

This study investigates how data analytics, public communication strategies, and conservation economics can be integrated to protect historic structures threatened by earthquakes, climate change, and environmental risks. From an architectural and engineering perspective, sensor-based structural health monitoring, vibration measurements, moisture/temperature diagnostics, and digital twin models are examined as tools for assessing risks and guiding intervention decisions. From a communication standpoint, the study analyzes how public awareness campaigns, crisis communication, community engagement, and cultural value narratives influence the success of conservation projects. In the marketing and business dimension, it evaluates restoration funding models, sponsorship strategies, culture economy potentials, and the transformation of heritage conservation into a branding asset. The paper concludes that heritage conservation should be understood as a data-driven, socially engaged, and economically sustainable management model, rather than exclusively a technical engineering task.

Keywords: Structural Health Monitoring, Historic Buildings, Conservation Economics, Digital Twin, Crisis Communication

Giriş

Depremler, iklim değişikliği, sel ve nem artışı gibi çevresel tehditler, tarihi yapıların korunması sürecini günümüzde daha karmaşık hâle getirmiştir. Bu nedenle kültürel mirasın korunması artık yalnızca restorasyon tekniklerinden ibaret değildir; veri analitiğine dayalı risk izleme teknolojileri, toplumsal farkındalık oluşturma süreçleri ve ekonomik olarak sürdürülebilir koruma modelleriyle bütünleşik ilerleyen çok disiplinli bir yönetim yaklaşımı gerektirmektedir. Yapısal sağlık izleme (Structural Health Monitoring–SHM), sensör tabanlı veri toplama, titreşim ölçümleri, sıcaklık–nem analizleri ve dijital ikiz teknolojileri tarihi yapıların hassas noktalarını erken tespit ederek müdahale planlarının doğruluğunu artırmaktadır (Aktas & Kijewski-Correa, 2021). Bununla birlikte risk altındaki yapılar, teknik çözümlerin yanı sıra güçlü bir toplumsal iletişim stratejisi gerektirir. Yerel halkın bilinçlendirilmesi, kriz anlarında doğru bilginin aktarılması ve sosyal medya üzerinden yürütülen farkındalık kampanyaları, koruma projelerinin başarısında belirleyici rol oynamaktadır. Ekonomik boyutta ise koruma projelerinin finansmanının sürdürülebilir olması, fonların çeşitlendirilmesi, sponsorluk stratejileri ve kültürel mirasın ekonomik bir marka değerine dönüştürülebilmesi önem kazanmaktadır. Bu çalışma, risk altındaki tarihi yapıların korunmasını teknik bir mühendislik sürecinden çıkararak veri odaklı, iletişim temelli ve ekonomik olarak sürdürülebilir bütüncül bir model içerisinde ele almaktadır.

1. Kavramsal Çerçeve

1.1. Veri Analitiği ve Yapısal Sağlık İzleme (SHM)

Yapısal sağlık izleme sistemleri, tarihi yapıların fiziksel davranışlarını gerçek zamanlı veri analizleri ile izlemeyi ve bozulma eğilimlerini erken aşamada tespit etmeyi amaçlar. Özellikle deprem riski altındaki bölgelerde titreşim analizleri, modal şekil değişimleri, çatlak ilerleme sensörleri, sıcaklık–nem kayıtları ve yer hareketi ölçümleri tarihi yapıların kırılgan bölgelerinin belirlenmesinde kritik rol oynar (Catbas et al., 2020). Son yıllarda dijital ikiz (digital twin) teknolojisiyle SHM verilerinin birleşmesi, yapının fiziksel davranışının dijital ortamda sürekli simüle edilmesine olanak tanımış; böylece risk tahminleri daha bilimsel ve veriye dayalı hâle gelmiştir.

Bu yaklaşım, müdahale kararlarında sezgisel yöntemlerden çok daha güvenilir ve şeffaf bir mühendislik süreci sunar. Veri analitiği tabanlı karar destek sistemleri sayesinde restorasyon ekipleri farklı senaryoları karşılaştırabilir, en düşük riskli müdahale alternatiflerini belirleyebilir ve yapının zaman içindeki davranışını izleyerek uzun vadeli koruma stratejileri geliştirebilir.

1.2. Görsel İletişim ve Dijital Temsillerin Kadın Üzerindeki Etkisi

Tarihi yapıların korunması yalnızca uzmanların teknik çalışmalarıyla sürdürülebilecek bir süreç değildir; yerel halka doğru bilgi aktarımı, kültürel değerlerin neden korunması gerektiğinin anlatılması ve risk anlarında etkili kriz iletişimi stratejilerinin uygulanması gereklidir. Kültürel mirasın korunmasına yönelik toplumsal katılımın artması, projelerin meşruiyetini ve uzun vadeli başarısını artırmaktadır (Jigyasu, 2019).

Dijital iletişim araçları bu süreçte önemli avantajlar sağlamaktadır. Sosyal medya farkındalık kampanyaları, kültürel değer anlatıları, kısa belgeseller, interaktif haritalar, afet anında bilgilendirme mesajları ve katılımcı dijital platformlar toplumun mirasa olan duygusal bağını güçlendirmekte; gönüllü katılım oranlarını yükseltmektedir. Ayrıca kriz iletişimi stratejilerinin doğru uygulanması, afet sonrasında bilgi kirliliğini azaltarak toplumsal güveni artırmakta ve koruma faaliyetlerinin hızlandığı kritik dönemlerde koordinasyonu kolaylaştırmaktadır.

1.3. Tüketim Kültürü ve Yorgunluğun Ticarileştirilmesi

Koruma ekonomisi, tarihi yapıların sürdürülebilir finansman modelleriyle korunmasını konu alan yeni bir yaklaşımdır. Kamu fonlarının yetersiz kaldığı durumlarda uluslararası hibeler, özel sektör sponsorlukları, kültür odaklı sosyal girişimler, ziyaretçi odaklı gelir modelleri ve kültürel mirasın markalaşma potansiyeli koruma faaliyetlerine finansal kaynak sağlar (Throsby, 2018).

Tarihi yapıların dijital temsili (dijital ikiz, sanal tur, dijital sergi) marka değerini artırarak ek finans kaynaklarının yaratılmasını kolaylaştırmaktadır. Ayrıca kültür ekonomisi yaklaşımına göre; korunan miras alanları çevre esnafına, turizme, hizmet sektörüne ve yerel ekonomiye doğrudan ekonomik değer kazandırmaktadır. Dolayısıyla koruma yalnızca maliyet oluşturan bir süreç değil, aynı zamanda ekonomik bir yatırım alanıdır.

2. Yöntem

Bu çalışma, nitel araştırma yaklaşımına dayalı olarak tasarlanmış kavramsal bir analiz çalışmasıdır. Modern kent yaşamında kadınların deneyimlediği tükenmişlik olgusunun çok boyutlu yapısı nedeniyle araştırma, tek bir disiplinden ziyade mimarlık, iletişim ve işletme/marketing alanlarının kesişiminde yürütülmüştür. Nitel yaklaşım, özellikle toplumsal deneyimlerin, kültürel temsillerin, mekânsal algıların ve duygusal tepkilerin bütüncül olarak anlaşılması açısından uygun bir yöntem olarak görülmektedir (Creswell & Poth, 2018).

Çalışmanın analiz çerçevesi üç ana disiplin üzerinden yapılandırılmıştır:

- Mimarlık, kentsel mekânın stres üretme biçimlerini, kamusal alanların tasarımını, gündelik kent ritmi ile beden-mekân ilişkisini değerlendirmek üzere ele alınmıştır. Kadınların kentsel mekânla etkileşimlerinde güvenlik, erişilebilirlik, hareketlilik ve mekânsal yorgunluk gibi boyutlar literatür doğrultusunda incelenmiştir (Kern, 2020).
- İletişim bilimleri, dijital temsillerin ve görsel kültürün kadınların psikolojik yükünü nasıl etkilediğini analiz etmek amacıyla kullanılmıştır. Bu kapsamda medya içerikleri, sosyal ağ pratikleri, idealize edilmiş beden ve başarı imgeleri, "görsel performans kültürü" bağlamında değerlendirilmiştir (Gill & Orgad, 2022).
- İşletme/Marketing, tüketim kültürünün kadınların tükenmişlik deneyimini nasıl metalaştırdığını açıklamak için kullanılmıştır. Duygusal pazarlama stratejileri, wellness endüstrisi ve "öz-bakım ekonomisi" literatürü üzerinden kavramsal bir inceleme yapılmıştır (Rottenberg & Fraser, 2021).

Veriler; uluslararası hakemli dergiler, raporlar, kitaplar ve güncel bilimsel yayınlar temel alınarak gerçekleştirilen kapsamlı literatür taraması ile toplanmıştır. Literatür taraması Scopus, Web of Science, Google Scholar ve SpringerLink gibi uluslararası veri tabanları kullanılarak yürütülmüş; 2018–2024 yılları arasındaki güncel çalışmalar önceliklendirilmiştir. Elde edilen kaynaklar, kavramsal karşılaştırma ve tematik analiz yoluyla değerlendirilmiş; disiplinler arası kavramlar benzerlikler ve farklılıklar temelinde karşılaştırılarak bütüncül bir analiz çerçevesi oluşturulmuştur (Nowell et al., 2017).

Çalışma nitel içerik analizi yaklaşımına dayalı olduğu için herhangi bir saha araştırması, anket ya da istatistiksel test uygulanmamıştır. Bu tercihin temel nedeni, kentsel tükenmişlik, dijital temsiller ve tüketim kültürü gibi fenomenlerin teorik tartışmalar üzerinden ele alınmasının araştırmanın amacına daha uygun olmasıdır. Bu kapsamda yöntem, karmaşık sosyal süreçleri açıklamaya yönelik çok katmanlı bir disiplinler arası analiz olarak yapılandırılmıştır.

3. Bulgular

3.1. SHM ve Dijital İkiz Modellerinin Risk Yönetimine Katkısı

Araştırma bulguları, yapısal sağlık izleme (SHM) yöntemleri ile dijital ikiz modellerinin entegrasyonunun kültürel miras yapılarının risk yönetiminde yeni bir standart oluşturduğunu ortaya koymaktadır. Titreşim sensörleri, çatlak ilerleme ölçerler, nem–sıcaklık vericileri, ivmeölçerler ve çevresel izleme istasyonları gibi sensör sistemlerinden elde edilen veriler, yapıların günlük, mevsimsel ve afet kaynaklı davranış değişimlerini yüksek hassasiyetle takip edebilmeyi mümkün kılmaktadır. Bu sensör verileri, dijital ikiz modellerine aktarıldığında yapı, gerçek zamanlı dijital bir simülasyon olarak yeniden üretilmekte; çatlak ilerlemesi, deformasyon, malzeme yorulması, termal genleşme ve taşıyıcı elemanlardaki zayıflık gibi risk unsurları erken aşamada belirlenebilmektedir.

Dijital ikiz modellerinin restorasyon süreçlerine sağladığı en önemli katkılardan biri, farklı müdahale senaryolarının simülasyonlarla önceden test edilebilmesidir. Böylece restorasyon ekipleri, yapıya en az zarar verecek yöntemleri seçebilmekte; geleneksel restorasyon sürecinde mevcut olan belirsizlikler önemli ölçüde azalmaktadır. Bulgular, SHM destekli erken uyarı sistemlerinin büyük ölçekli hasarların önlenmesinde kritik rol oynadığını; dijital ikiz teknolojisinin ise mühendislik temelli koruma kararlarını daha güvenilir ve veri odaklı hâle getirdiğini göstermektedir (Catbas et al., 2020).

3.2. Toplum Temelli İletişim ve Koruma Süreçlerine Etkisi

Çalışmanın ikinci bulgusu, toplumsal iletişim stratejilerinin koruma projelerinin başarısı üzerinde doğrudan belirleyici olduğunu ortaya koymaktadır. Yerel toplulukların tarihi yapıların kültürel değeri, risk durumu ve korunma gerekliliği hakkında bilgi sahibi olması vandalizm, bilinçsiz kullanım, yanlış müdahale ve afet sonrası bilgi kirliliği gibi sorunları önemli ölçüde azaltmaktadır. Bulgular, toplumsal farkındalığın yüksek olduğu bölgelerde koruma çalışmalarının hem daha hızlı hem daha sürdürülebilir biçimde yürütüldüğünü; gönüllü katılım oranlarının arttığını ve yerel kurumlarla iş birliğinin güçlendiğini göstermektedir.

Sosyal medya kampanyaları, kısa belgeseller, dijital sergiler, yerel halk eğitim programları ve risk anında kullanılan kriz iletişimi stratejileri kültürel mirasın toplumsal sahiplenmesini artırmaktadır. Dijital iletişim araçlarının, risk altındaki yapıların durumuna ilişkin "şeffaf bilgi akışı" sağlaması, projelere duyulan güveni ve destek oranını yükseltmektedir. Ayrıca afet sonrası kriz iletişimi, hangi yapıların hasar gördüğü, güvenlik açısından hangi bölgelerin risk taşıdığı ve hangi müdahalelerin yapılması gerektiği konusunda hızlı ve doğru bilgi sağlayarak hem toplumsal güvenliği artırmakta hem de koruma ekiplerinin koordinasyonunu kolaylaştırmaktadır (Jigyasu, 2019).

Bu bulgular ışığında, koruma projelerinin yalnızca teknik uzmanlığa değil; doğru planlanmış, toplum merkezli iletişim süreçlerine de ihtiyaç duyduğu görülmektedir. Toplumsal katılım, yalnızca destekleyici bir unsur değil, koruma sürecinin ayrılmaz bir bileşeni hâline gelmiştir.

3.3. Ekonomik Sürdürülebilirlik ve Koruma Projelerinin Marka Değeri

Araştırma bulguları, koruma projelerinin ekonomik sürdürülebilirliğinin restorasyon çalışmalarının devamlılığını belirleyen temel faktörlerden biri olduğunu göstermektedir. Geleneksel kamu kaynaklarının tek başına yeterli olmadığı koruma projelerinde dijital temsiller, sanal turlar, dijital sergiler, tematik kültür rotaları, bağış kampanyaları ve marka iş birlikleri gibi yeni finansman modelleri güçlü bir gelir akışı yaratmaktadır.

Dijital ikiz modellerinin yalnızca teknik bir koruma aracı değil, aynı zamanda güçlü bir görünürlük stratejisi sunduğu bulgulanmıştır. Dijital ikiz üzerinden sunulan şeffaf veri paylaşımı, kurumsal sponsorların projelere güven duyarak yatırım yapmasını kolaylaştırmakta; böylece koruma projelerinin marka değeri artmaktadır. Kültürel mirasın dijitalleştirilmesi, fon sağlayıcı kurumlar

için "yenilikçi, modern ve teknolojik olarak güçlü" bir imaj yaratmakta ve projelerin uluslararası fonlardan destek alma olasılığını yükseltmektedir (Throsby, 2018).

Bulgular ayrıca, korunan kültürel mirasın yerel ekonomiye doğrudan katkı sağladığını göstermektedir:

- dijital turizm gelirleri,
- kültürel girişimler,
- ziyaretçi deneyimine dayalı ürün ve hizmet modelleri,
- sponsorluk paketleri,
- yerel işletmelerin ekonomik canlılığı

koruma projelerini sürdürülebilir bir ekonomik döngüye dönüştürmektedir.

Genel olarak, tarihi yapıların korunması yalnızca kültürel bir sorumluluk değil; ekonomik açıdan da karşılıklı değer üreten bir yatırım alanı olarak ortaya çıkmaktadır.

Sonuç

Bu çalışma, risk altındaki tarihi yapıların korunmasının tek boyutlu bir restorasyon süreci değil; veri analitiği, toplumsal iletişim ve koruma ekonomisinin bütünleştiği çok katmanlı bir yönetim modeli olduğunu ortaya koymuştur. Yapısal sağlık izleme (SHM) sistemleri ve dijital ikiz teknolojilerinin kullanımı, kültürel mirasın fiziksel durumunu nesnel, sürekli ve yüksek doğrulukla izlemeyi mümkün kılmakta; böylece risklerin erken aşamada saptanarak büyük ölçekli hasarların önüne geçilmesini sağlamaktadır. Bu bulgu, geleneksel gözleme dayalı koruma yöntemlerinin yerini veriye dayalı karar destek mekanizmalarının aldığı yeni bir koruma paradigmasını işaret etmektedir.

Çalışmanın iletişim boyutu, teknik müdahalelerin toplumsal farkındalık olmadan tam anlamıyla etkili olamayacağını göstermiştir. Yerel halkın katılımı, doğru kriz iletişimi, dijital farkındalık kampanyaları ve kültürel hikâye anlatımı yöntemleri, miras alanlarına yönelik duygusal bağlılığı artırarak projelerin sosyal sürdürülebilirliğini güçlendirmektedir. Bu durum, kültürel mirasın yalnızca uzmanların koruduğu bir nesne değil, toplumun birlikte yaşattığı kolektif bir değer olduğunu ortaya koymaktadır.

Ekonomik bulgular ise koruma projelerinin sürdürülebilirliğinin büyük ölçüde finansman çeşitliliğine bağlı olduğunu göstermektedir. Dijital temsillerin ve dijital ikiz modellerinin yükselen marka değeri, ulusal ve uluslararası fonlara erişimi kolaylaştırmakta; özel sektör sponsorluklarını artırmakta ve dijital turizm gelirleri için yeni fırsatlar yaratmaktadır. Böylece kültürel mirasın korunması, ekonomik açıdan da geri dönüş sağlayan stratejik bir yatırım alanına dönüşmektedir. Koruma ekonomisinin gelişimi, projelerin uzun vadeli ve bağımsız bir finansal yapıya kavuşmasını desteklemektedir.

Genel olarak çalışma, üç disiplinin entegrasyonuyla elde edilen bütüncül yaklaşımın; teknik doğruluk, toplumsal kabul ve ekonomik sürdürülebilirlik arasında dengeli bir çerçeve sunduğunu göstermektedir. Bu bütünleşik model, kültürel mirasın hem fiziksel olarak geleceğe aktarılmasını hem de toplumsal bilinç, ekonomik değer ve kültürel süreklilik açısından desteklenmesini sağlayan çağdaş bir koruma anlayışı ortaya koymaktadır.

Bu nedenle geleceğin miras politikalarının; veriye dayalı izleme, toplum merkezli iletişim ve sürdürülebilir finansman modellerini birlikte ele alan çok disiplinli bir bakış açısını benimsemesi gerekmektedir. Bu yaklaşım, risk altındaki tarihi yapıların korunmasında küresel ölçekte uygulanabilir, güçlü ve uzun vadeli bir yol haritası sunmaktadır.

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SANAL GERÇEKLİK (VR) SİMÜLASYONLARININ ENDÜSTRİ 4.0 EĞİTİMİNDEKİ ROLÜ

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ÖZET

Endüstri 4.0'ın getirdiği dijital dönüşüm, üretim süreçlerini kökten değiştirmekte ve bu durum, mühendislerin sahip olması gereken teknik becerilere yönelik talepleri artırmaktadır. Geleneksel eğitim modelleri, özellikle pahalı laboratuvar ekipmanlarına dayanan uygulamalı eğitimler, bu yeni yetkinlikleri kazandırmada yetersiz kalmaktadır. COVID-19 pandemisi, özellikle pratik eğitimde uzaktan erişimin zorluklarını ortaya çıkararak yenilikçi pedagojik yaklaşımlara olan ihtiyacı pekiştirmiştir. Bu bağlamda, Sanal Gerçeklik (VR) tabanlı simülasyonlar ve uzaktan erişimli "Sanal Öğrenme Fabrikaları" (VLF), mühendislik eğitiminde sürdürülebilir ve etkili bir çözüm olarak öne çıkmaktadır.Sanal Gerçeklik, öğrencilere gerçek dünya endüstriyel senaryolarını taklit eden, yüksek düzeyde sürükleyici ve etkileşimli bir öğrenme ortamı sunar. Öğrenciler, maliyetli ekipmanlara zarar verme veya elektrik çarpması gibi fiziksel riskler olmaksızın, tehlikeli olabilecek (örn. CNC yangın söndürme) veya karmaşık prosedürleri defalarca güvenli bir şekilde uygulayabilirler. Yapılan çalışmalar, bu metodolojilerin etkinliğini doğrulamaktadır. Sistem Kullanılabilirlik Ölçeği (SUS) testleri ve deneysel değerlendirmeler, VR tabanlı eğitim araçlarının öğrenciler tarafından yüksek oranda (%85, %90) kabul gördüğünü ve "iyi" kullanılabilirlik puanları (örn. 74.6) aldığını göstermektedir. VR ile eğitim alan grupların, geleneksel yöntemlerle eğitim alan gruplara kıyasla görevleri daha hızlı ve daha az hata ile tamamladığı kanıtlanmıştır. Sonuç olarak, VR simülasyonları, dijital ikizler ve siber güvenlik gibi Endüstri 4.0'ın temel bileşenlerini entegre eden, motivasyonu artıran ve sürdürülebilir beceri kazanımını sağlayan zorunlu ve mantıklı bir eğitim aracı olarak konumlanmaktadır.

Anahtar Kelimeler: Sanal Gerçeklik (VR), Endüstri 4.0, Mühendislik Eğitimi, Uzaktan Laboratuvar, PLC Programlama

THE ROLE OF VIRTUAL REALITY (VR) SIMULATIONS IN INDUSTRY 4.0 EDUCATION

ABSTRACT

The digital transformation associated with Industry 4.0 is fundamentally reshaping production processes and increasing the demand for advanced technical competencies among engineers. Traditional pedagogical models—particularly hands-on training dependent on expensive laboratory equipment—have become insufficient for equipping learners with these newly required skills. The COVID-19 pandemic further highlighted the limitations of remote access to practical training, reinforcing the need for innovative educational approaches. In this context, Virtual Reality (VR) simulations and remote-access "Virtual Learning Factories" (VLFs) have emerged as sustainable and effective solutions within engineering education. Virtual Reality provides students with an immersive and interactive environment that accurately replicates real-world industrial scenarios. Learners can repeatedly and safely practice potentially hazardous (e.g., CNC fire suppression) or complex procedures without risking damage to costly equipment or exposure to physical hazards such as electrical shock. Recent studies confirm the effectiveness of these methodologies. System Usability Scale (SUS) assessments and experimental evaluations indicate that VR-based educational tools achieve high levels of student acceptance (e.g., 85%, 90%) and receive "good" usability scores (e.g., 74.6). Evidence also shows that learners trained through VR complete tasks more quickly and with fewer errors compared to those trained via traditional methods. Consequently, VR simulations have become an essential and rational educational tool that integrates key Industry 4.0 components—such as digital twins and cybersecurity—while enhancing learner motivation and supporting sustainable skill development.

Keywords: Virtual Reality (VR), Industry 4.0, Engineering Education, Remote Laboratory, PLC Programming

1. GİRİŞ

Endüstri 4.0 ile birlikte dijital dönüşüm, üretim sistemlerini ve iş süreçlerini kökten değiştirmektedir. Bu dönüşüm, mühendislerin sahip olması gereken teknik ve dijital becerileri de yeniden tanımlamakta, özellikle siber-fiziksel sistemler, dijital ikizler, siber güvenlik ve otomasyon gibi alanlarda yetkinlik ihtiyacını artırmaktadır (Adetunla ve ark., 2024). Geleneksel mühendislik eğitimi modelleri, özellikle pahalı fiziksel laboratuvar ekipmanlarına ve yüz yüze uygulamalara dayalı yapısıyla, bu yeni ve dinamik ihtiyaçları karşılamada yetersiz kalmaktadır. COVID-19 pandemisi, uzaktan eğitimin zorunlu hale gelmesiyle birlikte, pratik ve uygulamalı eğitimdeki bu açığı daha da görünür kılmıştır (Dunmoye ve ark., 2024). Bu zorluklar, eğitimde yenilikçi, erişilebilir ve sürdürülebilir pedagojik yaklaşımların benimsenmesini gerektirmektedir.

Bu bağlamda Sanal Gerçeklik (VR) tabanlı simülasyonlar, mühendislik eğitimi için hem sürdürülebilir hem de etkili bir çözüm olarak öne çıkmaktadır. VR, öğrencilere risk almadan (elektrik çarpması veya ekipman hasarı olmaksızın) deneyim kazanma, karmaşık ve tehlikeli senaryoları tekrarlama ve Endüstri 4.0'ın temel teknolojilerini bütünleşik bir ortamda öğrenme imkanı sunmaktadır (Sharma ve ark., 2023).

Bu çalışma, Endüstri 4.0 bağlamında mühendislik eğitiminde VR simülasyonlarının rolünü, etkinliğini ve gelecek potansiyelini inceleyen mevcut literatürü sistematik bir şekilde gözden geçirmeyi amaçlamaktadır. VR tabanlı eğitimin teorik temellerini, uygulama örneklerini, avantajlarını, karşılaşılan zorlukları incelenecektir.

2. EĞİTİMDE SANAL GERÇEKLİK

VR, bilgisayar sistemleri aracılığıyla inşa edilen, kullanıcıya yüksek düzeyde sürükleyicilik (immersion), gerçek zamanlı etkileşim (interaction) ve görsel gerçekçilik (fidelity) sağlayan simüle edilmiş bir ortamdır. VR teknolojileri, geleneksel iki boyutlu öğrenme materyallerinden koparak, öğrencilerin içeriğe üç boyutlu bir alanda katılımını sağlayan devrimci bir araçtır. Modern uygulamalar, görsel ve işitsel uyaranların yanı sıra, dokunsal geri bildirim (haptic feedback) ve hareket takibi (motion tracking) gibi öğeleri birleştirerek öğrenme deneyimini zenginleştirmektedir (Paszkiewicz ve ark., 2021).

2.1 Avantajlar ve Dezavantajlar

Eğitimde VR kullanımının en belirgin avantajı, öğrencilerin risk almadan pratik yapabilmelerine olanak tanımasıdır. Örneğin, cerrahi eğitimde veya tehlikeli endüstriyel işlemlerde, öğrenciler gerçek hayatta ciddi sonuçlar doğurabilecek hataları sanal ortamda güvenle yapıp bunlardan ders çıkarabilmektedir (Adetunla ve ark., 2024; Paszkiewicz ve ark., 2021). Ayrıca, VR teknolojisi öğrencilerin motivasyonunu ve derse katılımını artırmakta, soyut kavramların (örneğin moleküler yapılar veya karmaşık makineler) görselleştirilmesini sağlayarak bilişsel yükü yönetilebilir hale getirmektedir (Du ve ark., 2024). Zaman ve mekan kısıtlamalarını ortadan kaldırması, öğrencilerin normalde erişemeyecekleri tarihi yerleri veya endüstriyel tesisleri ziyaret etmelerine olanak tanır (Okul & Şimşek, 2025).

Bununla birlikte, teknolojinin getirdiği bazı dezavantajlar ve zorluklar da mevcuttur. Donanım ve yazılım maliyetlerinin yüksek olması, teknik altyapı eksikliği ve içerik oluşturma zorlukları yaygın engellerdir (Adetunla ve ark., 2024; Du ve ark., 2024). Ayrıca, uzun süreli kullanımda ortaya çıkabilen siber hastalık (cyber-sickness), göz yorgunluğu ve baş ağrısı gibi fiziksel rahatsızlıklar, öğrenme sürecini olumsuz etkileyebilir (Asitah ve ark., 2024). Eğitimcilerin bu teknolojiye uyum sağlaması ve müfredata entegrasyonu da ek bir pedagojik zorluk oluşturmaktadır (Terzulli ve ark., 2025).

2.2 Literatürden Örnek Çalışmalar ve Başarımlar

Sanal gerçekliğin farklı disiplinlerdeki eğitimsel etkinliğini gösteren ve kaynakça kapsamında incelenen 7 önemli çalışma aşağıda özetlenmiştir:

2.2.a. Kalça Artroskopisi Eğitiminde Beceri Kazanımı (Cerrahi Eğitim): Vivekanantha ve arkadaşları tarafından yapılan sistematik inceleme, VR simülatörlerinin kalça artroskopisi eğitimindeki etkinliğini değerlendirmiştir. Çalışma, VR eğitiminin yüksek yüz ve yapı geçerliliğine sahip olduğunu ortaya koymuştur.

• Sonuç/Başarım: Deneyimli cerrahlar simülatörde acemilerden daha iyi performans göstermiş (yapı geçerliliği), acemi kursiyerler ise tekrarlayan oturumlarla iyatrojenik doku hasarını azaltmış ve işlem sürelerini kısaltmıştır. VR, kadavra eğitimine göre daha uygun maliyetli ve güvenli bir alternatif olarak tanımlanmıştır (Vivekanantha ve ark., 2025).

2.2.b Arkeoloji ve Turist Rehberliği Eğitimi (Turizm Eğitimi) Okul ve Şimşek , turist rehberliği eğitiminde dört antik kenti (Priene, Miletos, Didim, Pergamon) kapsayan bir arkeoloji dersinde VR kullanımını yarı deneysel bir modelle test etmiştir. Solomon Dört Grup Modeli kullanılarak 70 öğrenci ile çalışılmıştır.

• Sonuç/Başarım: VR uygulaması kullanan deney gruplarının akademik başarı puanları ve bilgiyi akılda tutma (kalıcılık) düzeyleri, geleneksel yöntemlerle eğitim alan kontrol gruplarına göre anlamlı derecede yüksek bulunmuştur. Öğrenciler, "bulunma" hissi sayesinde mekanları deneyimleyerek öğrendiklerini belirtmiştir (Okul & Şimşek, 2025).

2.2.c. Endüstri 4.0 için Yeniden Yapılandırılabilir Üretim Sistemleri (Mühendislik Eğitimi): Salah ve arkadaşları, endüstri mühendisliği öğrencilerine karmaşık "Yeniden Yapılandırılabilir Üretim Sistemleri" (RMS) tasarımını öğretmek için Sanal Öğrenme Fabrikası (VLF) konseptini kullanmıştır. 50 öğrenci ile yapılan çalışmada, VR tabanlı eğitim alan grup ile geleneksel eğitim alan grup karşılaştırılmıştır.

• Sonuç/Başarım: VR tabanlı eğitim alan deney grubu, atölye zeminindeki gerçek konfigürasyon görevini kontrol grubuna göre daha kısa sürede ve daha az hatayla tamamlamıştır. İstatistiksel analizler, eğitim yönteminin tamamlanma süresi üzerinde anlamlı bir etkisi olduğunu göstermiştir (Salah ve ark., 2019).

2.2.d. Psikiyatri Hemşireliği Eğitimi (Sağlık Bilimleri): Ahn ve arkadaşları tarafından yapılan sistematik derleme, psikiyatri hemşireliği eğitiminde sürükleyici VR simülasyonlarının etkisini incelemiştir. İncelenen çalışmalarda empati, iletişim becerileri ve öğrenme motivasyonu gibi çıktılar değerlendirilmiştir.

• Sonuç/Başarım: VR simülasyonlarının iletişim becerilerini, empatiyi ve bilişsel katılımı artırmada etkili olduğu bulunmuştur. Özellikle, öğrencilerin psikiyatrik hastalarla etkileşime girerken yaşadıkları anksiyetenin azaldığı rapor edilmiştir. Ancak, bilgi edinimi (knowledge acquisition) konusunda geleneksel yöntemlere kıyasla her zaman anlamlı bir fark görülmemiştir (Ahn et al., 2025).

2.2.e. İç Mekan Tasarımında VR ve Kağıt Eskiz Karşılaştırması (Mesleki Eğitim): Qin ve Li, iç mekan tasarımı eğitiminde VR kullanımının öğrencilerin tasarım çıktılarına etkisini araştırmıştır. Öğrenciler ofis alanı tasarlarken VR araçlarını ve geleneksel kağıt eskiz yöntemlerini kullanmışlardır.

• Sonuç/Başarım: Çalışma, VR kullanımının tasarımda "oran" ve "kompozisyon" becerilerini geliştirdiğini, ancak "inovasyon" (yenilikçilik) puanlarının kağıt eskiz grubunda daha yüksek

olduğunu ortaya koymuştur. En yüksek tasarım kalitesi, önce kağıt eskiz yapılıp ardından VR kullanılan hibrit sıralamada elde edilmiştir (Qin & Li, 2022).

2.2.f. Endüstriyel Kontrol ve Elektrik Güvenliği (Teknik Eğitim): Atiaja ve arkadaşları, elektromekanik mühendisliği öğrencileri için endüstriyel kontrol panolarının montajını simüle eden çok seviyeli bir VR modülü geliştirmiştir. Çalışma, öğrencilerin elektrik çarpması korkusu olmadan pratik yapabilmelerini amaçlamıştır.

• Sonuç/Başarım: VR modülünü kullanan öğrenciler, kontrol ve manevra elemanlarını tanımada gelişme göstermiş, bağlantı hatalarını azaltmış ve devre montaj sürelerini kısaltmıştır. Öğrencilerin %90'ı sistemi pratik ve faydalı bulmuştur (Atiaja ve ark., 2023).

2.2.g. Disiplinlerarası Sağlık Eğitimi: Hemşirelik ve Eczacılık (Sağlık Bilimleri): Terzulli ve arkadaşları, sağlık eğitiminde disiplinler arası işbirliğini (IPE) geliştirmek amacıyla hemşirelik ve eczacılık öğrencileri için sürükleyici bir VR pilot çalışması gerçekleştirmiştir. Çalışmada, 20 hemşirelik ve 20 eczacılık öğrencisi, hiperkalemi (yüksek potasyum) ve akut böbrek hasarı olan sanal bir hastayı tedavi etmek için eşleştirilmiştir,. Öğrenciler, farklı fiziksel odalarda bulunmalarına rağmen, VR başlıkları aracılığıyla aynı sanal hastane odasında buluşmuş ve hastanın bakımı için işbirliği yapmışlardır.

• Sonuç/Başarım: Çalışma, VR tabanlı eğitimin öğrencilerin disiplinler arası bir ekip içinde çalışma konusundaki özgüvenlerini artırdığını göstermiştir. Katılımcıların tamamı, VR oturumunun ardından "disiplinler arası, ekip tabanlı bir ortamda bakım sağlama konusunda kendimi güvende hissediyorum" ifadesine katıldıklarını belirtmiştir. Ayrıca, senaryonun tekrar edilmesiyle performans puanlarında ve iletişim becerilerinde artış gözlemlenmiştir (Terzulli ve ark., 2025).

İncelenen çalışmalar, VR teknolojisinin tıp eğitiminden mühendisliğe, turizmden mesleki eğitime kadar geniş bir yelpazede akademik başarıyı, kalıcılığı ve uygulama becerilerini artırdığını göstermektedir. Özellikle riskli, pahalı veya erişimi zor senaryolarda VR, geleneksel yöntemlere göre üstün performans sergilemektedir. Ancak, teknolojinin tam potansiyeline ulaşması için donanım maliyetleri ve teknik sorunların aşılması, ayrıca pedagojik entegrasyonun dikkatle planlanması gerekmektedir.

3. ENDÜSTRİ 4.0 EĞİTİMİNDE SANAL GERÇEKLİK

Endüstri 4.0'ın temel bileşenlerinden biri olan Yeniden Yapılandırılabilir Üretim Sistemleri'nin (RMS) tasarımı ve işletimi, acemi mühendisler için anlaşılması zor konulardır. Salah ve arkadaşları tarafından yürütülen çalışma, VR tabanlı eğitimin öğrencilerin RMS konfigürasyonlarını anlamalarını önemli ölçüde kolaylaştırdığını ortaya koymuştur. Çalışma sonuçlarına göre, VR eğitimi alan deney grubu, gerçek atölye ortamındaki konfigürasyon görevlerini, geleneksel eğitim alan gruba göre daha kısa sürede ve daha az hata ile tamamlamıştır (Salah ve ark., 2019). Bu durum, VR'ın karmaşık teorik kavramların pratik becerilere dönüştürülmesindeki etkinliğini kanıtlamaktadır.

Endüstri 4.0 sadece mekanik üretimden ibaret değildir; Nesnelerin Endüstriyel İnterneti (IIoT), bulut bilişim ve siber güvenlik gibi katmanları da içerir. Fuertes ve arkadaşları, öğrencilerin bu katmanları bütünleşik olarak deneyimleyebilmesi için VR destekli bir "Dijital İkiz" (Digital Twin) ortamı geliştirmiştir. Bu ortamda öğrenciler, sanal bir endüstriyel tesis üzerinde otomasyon, uzaktan izleme, bulut bilişim ve siber güvenlik (firewall yapılandırması vb.) görevlerini yerine getirmişlerdir. Öğrencilerle yapılan anketler, sistemin kullanılabilirliğinin yüksek olduğunu (SUS skoru: 74.6) ve motivasyonu artırdığını göstermiştir (Fuertes ve ark., 2021). Benzer şekilde Morán ve arkadaşları, öğrencilerin sanal makineler üzerinden gerçek

PLC'leri simüle edebildiği ve hem evden (offline) hem de laboratuvar ekipmanlarına uzaktan bağlanarak (online) çalışabildiği hibrit bir platform sunmuştur (Morán ve ark., 2024).

Endüstriyel süreçlerin kontrolünde teorik bilgi ile pratik uygulama arasındaki boşluğu kapatmak için "Döngüdeki Donanım" (Hardware-in-the-Loop - HIL) tekniği kritik bir rol oynamaktadır. Ortiz ve arkadaşları, bira üretim sürecini sanallaştırarak, öğrencilerin fiziksel bir PLC (S7-1200) ve SCADA sistemi üzerinden sanal fabrikayı gerçek zamanlı kontrol etmelerini sağlayan yenilikçi bir sistem geliştirmiştir. Bu entegrasyon sayesinde öğrenciler, sensörlerden gelen giriş sinyallerini ve aktüatörlerdeki çıkış tepkilerini sanal ortamda gözlemleyerek, endüstriyel kontrol süreçlerini güvenli bir şekilde deneyimleme ve müdahale etme şansı bulmuşlardır (Ortiz ve ark., 2024).

Endüstri 4.0 ortamlarında iş sağlığı ve güvenliği (İSG) eğitimi, çalışanların risk farkındalığını artırmak için hayati önem taşımaktadır. Qawqzeh ve arkadaşları tarafından 200 katılımcı ile yürütülen yarı deneysel çalışma, VR tabanlı İSG eğitiminin geleneksel yöntemlere kıyasla üstünlüğünü ortaya koymuştur. Çalışma sonucunda, VR eğitimi alan grubun güvenlik bilgisinde %25, risk farkındalığında ise %30 oranında artış gözlemlenmiştir. Ayrıca, VR grubunun Endüstri 4.0 senaryolarına uyum sağlama yeteneği ve öz yeterlilik algısı, kontrol grubuna göre anlamlı derecede yüksek bulunmuştur (Qawqzeh ve ark., 2025).

Karmaşık makine operatörlüğü eğitiminde VR, yetkinlik kazanma süresini kısaltmakta ve hata oranlarını düşürmektedir. Carretero ve arkadaşları, CNC freze makinesi ve matkap montajı gibi endüstriyel görevler için geliştirdikleri VR eğitim metodolojisi ile somut başarılar elde etmiştir. Geleneksel eğitim ile karşılaştırıldığında, VR eğitimi alan çırakların makineyi kullanma konusundaki güven düzeyleri %35'ten %96'ya yükselmiştir. Ayrıca, görev tamamlama süresi ortalama 28 dakikadan 19 dakikaya düşmüş ve ortalama hata sayısı 4'ten 2'ye inerek operasyonel verimlilikte belirgin bir iyileşme sağlanmıştır (Carretero ve ark., 2021).

Benzer bir yaklaşımla Paszkiewicz ve arkadaşları, CNC makinelerinde çıkabilecek yangınlara müdahale prosedürlerini (acil durdurma, alarm aktivasyonu, doğru yangın söndürücü seçimi) öğreten bir VR eğitim istasyonu geliştirmiştir. Çalışma, katılımcıların tekrarlayan sanal denemelerle müdahale sürelerini kısalttığını ve kriz anında doğru karar verme yetkinliklerini güvenli bir ortamda geliştirdiğini göstermiştir. Bu tür simülasyonlar, gerçek hayatta yapılması tehlikeli veya maliyetli olan eğitimlerin sanal dünyada risksiz bir şekilde gerçekleştirilmesine olanak tanır (Paszkiewicz ve ark., 2021).

4. SANAL GERÇEKLİK ÇALIŞMALARININ BAŞARIM TEST YÖNTEMLERİ

4.1. Kontrollü Deneysel Tasarımlar: Çoğu çalışma, katılımcıları "Deney Grubu" (VR kullananlar) ve "Kontrol Grubu" (Geleneksel yöntem, video veya kağıt kullananlar) olarak ayırmıştır. Örneğin, Solomon Dört Grup Modeli kullanılarak hem ön testin etkisini kontrol eden hem de VR'ın etkisini ölçen tasarımlar mevcuttur.

4.2. Objektif Performans Metrikleri: Özellikle mühendislik ve cerrahi eğitimlerinde, başarı sübjektif görüşlerle değil, tamamlama süresi (saniye/dakika), hata sayısı, çarpışma sayısı ve hareket mesafesi gibi sistem tarafından kaydedilen verilerle ölçülmüştür.

4.3. Psikometrik ve Duyuşsal Ölçekler: Tıp ve çevre eğitimi gibi alanlarda, VR'ın anksiyete (STAI-Y), ağrı (VAS), şüphecilik ve harekete geçme niyeti üzerindeki etkisi standartlaştırılmış ölçeklerle test edilmiştir.

4.4. Bilgi Transferi ve Kalıcılık Testleri: Bazı çalışmalar, eğitimin hemen ardından yapılan testlerin ötesine geçerek, haftalar sonra yapılan kalıcılık (retention) testleri veya sanal ortamda öğrenilen becerinin gerçek dünyaya (transfer) aktarılıp aktarılmadığını ölçmüştür.

Tablo 1'de farklı disiplinlerden seçilmiş ve incelenen çalışmaların başarımlarını nasıl test ettiğini ve elde ettikleri temel sonuçları özetlemektedir.

Yazar / Çalışma	Alan / Konu	Test Yöntemi ve Kullanılan Araçlar	Ölçülen Başarım Kriterleri	Temel Sonuç / Bulgular
Okul ve Şimşek	Turizm / Arkeoloji	Yarı deneysel, Solomon Dört Grup Modeli (Öntest-sontest ve kalıcılık testi).	Akademik başarı puanları, bilginin akılda kalıcılığı (retention).	VR grubu, geleneksel yöntemle (slayt) ders işleyen gruba göre hem akademik başarıda hem de bilgiyi hatırlamada istatistiksel olarak anlamlı düzeyde daha yüksek puan almıştır.
Salah ve ark.	Endüstri Müh. (RMS)	Kontrol gruplu deney (n=50). Geleneksel sınıfa karşı VR tabanlı "Sanal Öğrenme Fabrikası".	Görev tamamlama süresi, konfigürasyon doğruluğu (hata sayısı).	VR grubu, karmaşık üretim sistemi tasarımlarını kontrol grubuna göre daha kısa sürede ve daha az hatayla tamamlamıştır.
Martínez-Gutiérrez ve ark.	Robotik / Operatör Eğitimi	Üç gruplu deney: 1) Gerçek Robot, 2) VR, 3) PC Ekranı (2D). Beceri transferi testi.	Gerçek bir robotu parkurda sürme süresi ve çarpışma (hata) sayısı.	En iyi gelişimi gerçek robotla çalışanlar (%47) göstermiştir. Ancak VR grubu (%38), sadece ekran başında çalışanlara (%28) göre gerçek dünyaya beceri transferinde daha başarılı olmuştur.
Claudel ve ark.	Tıp / Prenatal Tanı	Karşılaştırmalı çalışma (Önce-Sonra). STAI-Y ve VAS ölçekleri.	Anksiyete seviyesi ve işlem sırasındaki ağrı algısı.	İnvaziv işlemler sırasında VR gözlüğü kullanan kadınların anksiyete puanı medyan 7 puan, ağrı puanı ise 2 puan daha düşük çıkmıştır.
Qawqzeh ve ark.	İş Sağlığı ve Güvenliği	Yarı deneysel (n=200). Müdahale ve kontrol grubu karşılaştırması.	Güvenlik bilgisi, risk farkındalığı, öz yeterlilik algısı.	VR eğitimi alan grubun risk farkındalığı %30, güvenlik bilgisi %25 artmıştır. Liderlik desteği ve iletişim algısında da iyileşme görülmüştür.
Qin ve Li	Mesleki Eğitim / İç Mimarlık	Karşılaştırmalı analiz. Kağıt eskiz grubu (A) vs. VR grubu (B) vs. Hibrit gruplar.	Tasarım çıktı puanları: Oran (Proportion), Kompozisyon ve İnovasyon.	VR, "oran" ve "kompozisyon" becerilerini geliştirirken, "inovasyon" puanları kağıt eskiz grubunda daha yüksek çıkmıştır. En iyi sonuç "önce kağıt eskiz, sonra VR" sıralamasında alınmıştır.
Alex ve ark.	Çevre Eğitimi / İklim	Üç seviyeli deney (AR, VR, 2D ekran).	Buradalık hissi (Local vs. Telepresence), şüphecilik, eyleme geçme niyeti.	VR, kullanıcıyı uzak ortama taşıyarak (telepresence) sorunu hissettirmede en iyisidir. AR ise sorunu kullanıcının ortamına getirerek şüpheciliği azaltmada daha etkilidir.
Ortiz ve ark.	Endüstriyel Otomasyon	Hardware-in-the-Loop (HIL) tekniği ile entegre VR ve SCADA sistemi.	Sistem kullanılabilirlik ölçeği (SUS) ve memnuniyet anketi.	Öğrenciler sistemin kullanılabilirliğini %85 oranında onaylamış; teorik bilgilerin gerçek zamanlı sanal bir fabrikada uygulanabilmesi motivasyonu artırmıştır.
Bateman ve ark.	Psikomotor Beceriler	Bayesian Ağı (BN) modellemesi ile 41 çalışmanın meta-analizi.	Öğrenme (görev başarısı) ve Transfer (yeni duruma aktarım).	Dokunsal geri bildirim (haptic feedback), görevi ilk öğrenme aşamasında başarıyı düşürse de (-%15), becerinin gerçek hayata transferini artırmaktadır (+%19).

Tablo 1: *İncelenen Çalışmalara ait Başarım Ölçme Yöntemleri ve Bulgular*

SONUÇ

Literatüre bakıldığında, VR teknolojisinin Endüstri 4.0 eğitiminde "ekstra" bir lüks değil, nitelikli iş gücü yetiştirmek için artık ihtiyaç haline gelen bir araç olduğu görülüyor. VR, öğrencilere robotlar, CNC makineleri, PLC'ler gibi pahalı endüstriyel ekipmanlara mekandan bağımsız erişim olanağı sunarak eğitimde fırsat eşitliğini güçlendiriyor ve "yaparak öğrenme" ilkesini dijital çağa uyarlıyor. Özellikle hata yapmanın çok maliyetli olabileceği endüstriyel süreçlerde, sanal ortamda kazanılan deneyim, gerçek üretim ortamındaki verimlilik ve güvenliği doğrudan artırma potansiyeli taşıyor. Bu nedenle geleceğin müfredatlarının yalnızca teorik bilgi aktarımına değil, VR ve Dijital İkiz teknolojileriyle desteklenen entegre sistem eğitimlerine odaklanması, endüstrinin ihtiyaç duyduğu yetkin mühendis profilini oluşturmak açısından kritik görünüyor. Geleceğin eğitim modeli; fiziksel ve dijital ortamların birbirini tamamladığı hibrit bir yapı olarak şekillenecek. Tehlikeli, maliyetli veya erişimi zor endüstriyel senaryolar söz konusu olduğunda ise VR, gönüllü bir seçenek olmaktan çıkıp vazgeçilmez bir standart olmaya doğru ilerliyor.

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ÇEVRESEL, EKONOMİK VE SOSYAL BOYUTLARIYLA SÜRDÜRÜLEBİLİR TARIM SİSTEMLERİ

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ÖZET

Tarım, gıda üretimi, ekonomik kalkınma ve doğal kaynakların korunması açısından temel bir konumdadır. Artan nüfus, iklim değişikliği, su kıtlığı ve toprak bozulması, tarımsal üretimi giderek daha kırılgan hâle getirmektedir. Geleneksel tarım yöntemleri geçmişte başarılı olsa da yoğun kimyasal kullanımı ve çevresel baskılar nedeniyle günümüz koşullarında sürdürülebilirlik açısından yetersiz kalmaktadır. Bu nedenle sürdürülebilir tarım, doğal kaynakların korunmasını, çevresel etkilerin azaltılmasını ve güvenli gıda üretimini esas alan bütüncül bir yaklaşım olarak önem kazanmıştır. Toprak, su ve enerji döngülerinden en verimli şekilde yararlanmayı hedefleyen bu sistemlerde yenilenebilir enerji kullanımı, organik gübreleme, örtü bitkileri ve çeşitlendirilmiş üretim teknikleri öne çıkmaktadır. Dünya genelinde dijital tarım uygulamaları, sensörler, veriye dayalı yönetim ve modern ıslah çalışmaları sürdürülebilir üretimi desteklemektedir. Ancak üreticilerin bilgi eksikliği, yüksek yatırım maliyetleri ve yeniliklere karşı isteksizlik gibi sınırlamalar, bu uygulamaların yaygınlaşmasını güçleştirmektedir. İklim değişikliğinin yol açtığı sıcaklık artışları, kuraklık, sel, zararlı ve hastalık baskısı sürdürülebilir uygulamaların gerekliliğini daha da artırmaktadır. Toprak sağlığını koruyan, su verimliliğini yükselten ve karbon tutulumunu destekleyen yöntemler tarım sistemlerini iklim risklerine karşı daha dayanıklı hâle getirmektedir. Sonuç olarak sürdürülebilir tarım; çevresel koruma, ekonomik dayanıklılık ve toplumsal refahı birlikte ele alan bir yaklaşım olup, geleceğe yönelik tarım politikalarının merkezinde yer alması gereken stratejik bir dönüşümü ifade etmektedir.

Anahtar Kelimeler: Sürdürülebilir tarım, Ekolojik denge, Yenilik ve yayılım süreçleri, Tarımsal sürdürülebilirlik politikaları

SUSTAINABLE AGRICULTURAL SYSTEMS IN ENVIRONMENTAL, ECONOMIC, AND SOCIAL DIMENSIONS

ABSTRACT

Agriculture occupies a central role in food production, economic development, and the preservation of natural resources. Rising population, climate change, water scarcity, and soil degradation are increasingly making agricultural production more vulnerable. Although traditional farming practices were effective in the past, their reliance on intensive chemical inputs and the associated environmental pressures render them insufficient for sustainability under current conditions. Consequently, sustainable agriculture has gained importance as a holistic approach that prioritizes the conservation of natural resources, the reduction of environmental impacts, and the production of safe food. These systems aim to optimize soil, water, and energy cycles, with practices such as renewable energy utilization, organic fertilization, cover cropping, and diversified production techniques being central. Globally, digital farming applications, sensors, data-driven management, and modern breeding programs are supporting sustainable production. However, limitations such as farmers' lack of knowledge, high investment costs, and reluctance to adopt innovations hinder the widespread implementation of these practices. Climate change–induced temperature increases, droughts, floods, and pest and disease pressures further emphasize the necessity of sustainable approaches. Methods that maintain soil health, enhance water efficiency, and promote carbon sequestration increase the resilience of agricultural systems to climate risks. In conclusion, sustainable agriculture represents a strategic transformation that integrates environmental protection, economic resilience, and societal well-being, and should occupy a central place in future agricultural policies.

Keywords: Sustainable agriculture, Ecological balance, Innovation and adoption processes, Agricultural sustainability policies

GİRİŞ

Tarım, gıda üretimini sağlayarak ve ekonomik kalkınmaya katkıda bulunarak insan yaşamının sürdürülmesinde temel bir rol oynamaktadır. Tüketicilerin güvenli gıdaya ulaşması, gıdaların raf ömrünü uzatmak amacıyla işlenmeleri, ekolojik dengenin ve tarımsal kaynakların korunması vb. gelişmeler tarımı önemli bir sektör haline getirmiştir. Dünyada nüfusun hızlı bir şekilde artması çevresel sorunları da beraberinde getirmektedir (Yılmaz ve Yücel, 2017). Son yıllarda iklim değişikliği, kaynak kıtlığı ve artan gıda talebi tarım sektörünün karşı karşıya kaldığı en önemli zorlukların başında gelmektedir. Bu talebin karşılanmasında yoğun girdili konvansiyonel (geleneksel) tarımsal uygulamalar önem kazanmıştır (Eryılmaz ve Kılıç,2018). Geleneksel tarım teknikleri geçmişte başarılı olsa da genellikle sürdürülemez çevresel etkilere, aşırı kimyasal girdiye ve verimsiz kaynak kullanımına neden olmaktadır. Ayrıca hızlı nüfus artışı ve iklim değişikliklerinin yaşandığı bir çağda ürün yönetimi ve kaynak bulmada zorluk yaşanmaktadır (Wang ve Li, 2025).

Sürdürülebilirlik kavramı, çevresel kaynakların sınırlı olduğu dünyada ekonomik büyüme ve kalkınmanın geleceğini güvence altına almak amacıyla ortaya çıkmıştır. Sürdürülebilir tarım, doğaya zarar vermeyen teknolojilerin kullanıldığı, uzun vadede verimi artırmayı amaçlayan, doğal kaynakların korunmasını sağlayan tarımsal üretim yöntemlerinin bütünüdür (Yılmaz ve Yücel, 2017). Sürdürülebilir tarımın dünyada önem kazanmasıyla birlikte çevreyi ve insan sağlığını korumayı hedefleyen bu sistemlerin yaygınlaştırılması giderek daha kritik bir hâl almıştır. En yaygın sürdürülebilir tarım sistemlerinden biri olan iyi tarım uygulamaları, her geçen gün daha fazla önem kazanmakta; yapılan işlemlerin kayıt altına alınmasını esas alan kontrollü bir tarımsal faaliyet olarak öne çıkmaktadır. İyi tarım uygulamalarında kullanılan zirai ilaç ve gübrenin miktarı, uygulama zamanı, uygulayıcının ismi, ürünün tür ve çeşidi gibi kayıtlar tutularak izlenebilirlik ve sürdürülebilirlik yerine getirilmiş olur (Eryılmaz ve Kılıç, 2018).

Sürdürülebilir tarım kavramı, tarımsal verimliliği en üst düzeye çıkarırken ekonomik istikrarı korumaya; aynı zamanda sınırlı doğal kaynak kullanımını ve zararlı çevresel etkileri en aza indirmeye dayanır. Tarımsal sürdürülebilirlik, herkes için sonsuza dek izlenmesi gereken toplumsal bir hedeftir ve genel ilkeler tarafından yönlendirilmelidir (Gerber, 1992).

Sürdürülebilir tarım sistemleri, mevcut toprak besin ve su döngülerinden, enerji akışlarından, faydalı toprak organizmalarından ve doğal zararlı kontrol mekanizmalarından maksimum düzeyde yararlanacak şekilde tasarlanır. Mevcut döngü ve akışlardan yararlanılarak çevresel zararlar önlenebilir ya da en aza indirilebilir. Bu sistemler ayrıca besleyici ve insan sağlığına zarar verebilecek maddelerle kontamine olmamış gıda üretmeyi hedefler. Sürdürülebilir tarım sistemlerinin bir diğer önemli boyutu ise yenilenebilir enerji kaynaklarının entegrasyonudur. Sürdürülebilir bir sistem biyolojik, jeotermal, hidroelektrik, güneş veya rüzgâr gibi yenilenebilir enerji kaynaklarını kullanır. Yeraltı suyunun yenilenme hızından fazla kullanılması gibi geri dönüştürülebilir kaynakların aşırı kullanımı rezervleri tüketir ve sürdürülemez. Dünyaya ulaşan güneş radyasyonu doğadaki en temel yenilenebilir enerji kaynağıdır. Biyosistemi, okyanusu ve atmosfer akımlarını güçlendirir ve küresel iklimi etkiler (Omer, 2008). Yenilenebilir enerji kaynakları, özellikle kırsal alanlarda tarımsal üretimin sürdürülebilirliğini destekler; fosil yakıtlara olan bağımlılığı azaltarak çevresel etkileri en aza indirir. Böylece sürdürülebilir tarımın çevresel, ekonomik ve sosyal hedeflerine ulaşmasına katkıda bulunur.

Bilgi eksikliği, uygulamaların benimsenmesinde önemli bir engel oluşturmaktadır. Sürdürülebilir bir uygulamanın varlığına ilişkin bilgi eksikliği, uygulamanın maliyet ve faydalarına dair belirsizlikler ve uygulamanın nasıl gerçekleştirileceğine dair yetersiz bilgi, benimsemenin önünde önemli engeller yaratabilir. Bu sorunlar, üreticilerin sürdürülebilir

uygulamaları benimsemelerini teşvik eden tarımsal yayım programlarının geliştirilmesi açısından kritik sonuçlar doğurur. Bilgi eksikliklerini azaltmak, uygulamaların benimsenmesi ve sürdürülebilir tarım sistemlerinin geliştirilmesi önünde önemli bir engel oluştukları için öncelikli bir araştırma alanıdır (Reganold ve ark. 2011).

Günümüzde artan nüfus, iklim değişikliği ve doğal kaynakların azalması, tarımsal üretimde sürdürülebilirliği zorunlu hale getirmiştir. Bu bağlamda, sürdürülebilir tarımsal gelişmelerin hem yerel hem de küresel ölçekte değerlendirilmesi büyük önem taşımaktadır. Bu makalenin amacı, Türkiye ve dünyada sürdürülebilir tarımsal gelişmelerin tarihsel sürecini, mevcut uygulamalarını ve gelecek projeksiyonlarını analiz ederek; çevresel, ekonomik ve sosyal boyutlarda sürdürülebilirliğin tarımsal kalkınmaya etkilerini ortaya koymaktır.

1. Sürdürülebilir Tarım Kavramı

Sürdürülebilir tarım, ekonomik, çevresel ve sosyal hedefleri bütünleştirerek tarımsal üretimin uzun vadede devamlılığını sağlamayı amaçlayan bir yaklaşımdır (Hansen, 1996). Bu yaklaşım, tarımsal sistemlerin üretkenliğini korurken çevresel kaynakların ve toplumsal refahın sürdürülebilir biçimde kullanılmasına odaklanır (Ikerd, 1990). Sürdürülebilir uygulamalar, hem çevresel ve sosyal faydalar sağlamak hem de üreticilerin maliyetlerini düşürerek ekonomik getirilerini artırmak amacıyla geliştirilir. Uygulamaların maliyet-fayda dengesi farklılık gösterdiğinden, üreticilerin kararları ve yayım faaliyetlerinin etkinliği doğrudan etkilenir (Pannell, 2008). Bilgi eksiklikleri, uygulamanın varlığı, maliyeti, faydası ve uygulama yöntemleri hakkında karar alıcıların sahip olduğu sınırlı bilgiler, benimsenmenin önünde önemli bir engel oluşturmaktadır. Sürdürülebilir uygulamaların benimsenmesi iki sosyal süreçle açıklanabilir: yenilik ve iş birliği. Ekonomik faydaların maliyetleri aşan uygulamalarda yenilik ön plana çıkarken, sosyal faydaların kolektif çabayla sağlandığı uygulamalarda iş birliği temel rol oynar (Rogers, 2003; Ostrom, 1990). Yüksek öncelikli yenilik uygulamaları, bireysel faydalar nedeniyle daha kolay benimsenirken, yüksek öncelikli iş birliği uygulamaları kolektif hareket gerektirir. Öğrenme stratejileri ve sosyal ağlar, bilgi eksikliklerinin oluşumunu etkiler ve düşük fayda-yüksek maliyet uygulamalarda bilgi boşlukları daha yaygındır.

2. Türkiye ve Dünyada Yaşanan Gelişmeler

Dünyada tarım alanlarının azalması ve su kaynaklarının giderek daha fazla tehdit altına girmesi, küresel gıda güvenliği açısından ciddi bir sorun teşkil etmektedir. Özellikle iklim değişikliği, toprak erozyonu, su kıtlığı ve hava kirliliği gibi faktörler, tarımın verimli bir şekilde sürdürülebilmesi önünde büyük engeller oluşturmaktadır. Bu durumda, tarım politikalarının yeniden şekillendirilmesi, sürdürülebilir tarım tekniklerinin uygulanması ve verimli toprakların korunması, oldukça kritik bir hale gelmiştir. Brezilya ve İsrail gibi ülkeler, tarım verimliliğini artırmak için toprak ıslahı konusunda önemli adımlar atarken, Türkiye ve Çin gibi bazı ülkeler ise sınırlı tarım alanlarını başka kullanım alanlarına dönüştürme yoluna gitmişlerdir. Bu da bir yandan verimli toprakların kaybı, diğer yandan da üretim kapasitesinin azalması anlamına gelmektedir. Bu sorunun çözülmesi için daha etkili ve sürdürülebilir tarım yöntemlerinin benimsenmesi şarttır. Tarım sektöründe sürdürülebilirliğin sağlanabilmesi, büyük ölçüde teknolojik yeniliklerin ve modern üretim tekniklerinin etkin biçimde uygulanmasına bağlıdır. Bu kapsamda dijital tarım uygulamaları, su kaynaklarının rasyonel yönetimi ve toprak verimliliğini artırmaya yönelik ıslah çalışmaları, üretim süreçlerinin verimliliğini yükseltmekte ve kaynak kullanımını optimize etmektedir. Söz konusu gelişmeler, küresel ölçekte gıda güvenliğinin korunması açısından stratejik bir önem taşımaktadır (Turhan, 2005).

Tarımsal üretim süreçlerinde aşırı kimyasal girdi kullanımının ürün kalitesi ve çevre üzerindeki olumsuz etkilerini en aza indirmek ve çevresel sürdürülebilirliği sağlamak amacıyla, özellikle

gelişmiş ülkeler başta olmak üzere birçok ülkede sürdürülebilir tarım sistemlerinin uygulanması ve desteklenmesi teşvik edilmektedir. Finlandiya'da tarımsal faaliyetlerde su kaynaklarının neden olduğu çevresel kirliliğinin azaltılmasına, Almanya, İsviçre, Hollanda ve Fransa gibi ülkelerde ise tarıma elverişliliği düşük alanların üretim sürecine dâhil edilmesine yönelik politikalar kapsamında mali destek programları yürütülmektedir. Geleneksel tarım uygulamalarının karşı karşıya olduğu verimlilik, kaynak kullanımı ve çevresel sürdürülebilirlik sorunlarının aşılabilmesi amacıyla, büyük veri analitiği ve makine öğrenimi gibi yenilikçi teknolojiler geliştirilmiştir. Tarım alanlarının yoğun ve verimli kullanımında dünya liderlerinden biri konumunda bulunan Çin, söz konusu teknolojileri kapsamlı biçimde benimsemiş ve geliştirmiştir. Toprak sağlığı, hava koşulları ve nem düzeylerinin gerçek zamanlı izlenebilmesi için insansız hava araçları (dronlar), yapay zekâ algoritmaları ve nesnelerin interneti (IoT) tabanlı sistemler etkin biçimde kullanılmaktadır. Bu teknolojik yaklaşımlar, tarımsal üretim verimliliğinin artırılmasına ve karar verme süreçlerinin daha bilimsel temellere dayandırılmasına önemli katkılar sağlamaktadır (Wang ve Li, 2025).

Doğal kaynakların korunması ile çevresel zararları en aza indirgeyen, topraktaki karbon miktarını artıran, toprak erozyonunu azaltan, gıda kalitesini artırarak insan sağlığının ve gıda güvenliğinin üst seviyede tutulmasını sağlayan iyi tarım uygulamaları Türkiye' de ilk kez 2007 yılında başlamış olup üretici sayısı ve üretim alanı bakımından 2013 yılından itibaren önemli oranda artış yaşanmıştır (Kayişoğlu ve Türksoy, 2023).

Çizelge 1: 2007-2021 İyi Tarım Göstergeleri

Yıl	İl Sayısı	Üretici Sayısı	Üretim Alanı (Ha)	Üretim Miktarı (Ton)
2007	18	651	5.361	6.000
2021	63	10.265	389.485	6.162.544

Kaynak: (Anonim, 2022a)

3. Sürdürülebilir Tarım Sistemleri ve Temel Hedefler

Sürdürülebilir tarım sistemleri, mevcut toprak besin ve su döngülerinden, enerji akışlarından, faydalı toprak organizmalarından ve doğal zararlı kontrol mekanizmalarından maksimum düzeyde yararlanacak şekilde tasarlanır. Böylece çevresel zararlar önlenebilir veya en aza indirilebilir (Lichtfouse ve ark., 2009). Sistemler aynı zamanda besleyici ve insan sağlığına zarar vermeyecek şekilde güvenli gıda üretmeyi hedefler. Temel hedefler arasında; daha kârlı çiftlik gelirleri sağlamak, çevresel korumayı teşvik etmek ve çiftçi aileleri ile kırsal toplulukların yaşam kalitesini artırmak bulunur. Bu hedefler doğrultusunda toprak kalitesinin korunması ve iyileştirilmesi, tükenebilir kaynaklara bağımlılığın azaltılması ve çevresel risklerin minimize edilmesi büyük önem taşır. Ekolojik açıdan, sürdürülebilir tarım yoğun üretime rağmen çevre kalitesini korumayı hedefler. Yoğun hayvancılık ve sentetik gübre kullanımı, sera gazı emisyonlarına katkıda bulunur ve su ile toprak kalitesine zarar verir. Bunun aksine, sürdürülebilir uygulamalar, toprak ve su yönetimi, örtü bitkileri, ürün ve peyzaj çeşitliliği, agroforestry ve organik gübreleme gibi yöntemlerle çevresel riskleri azaltır. Ayrıca, sürdürülebilir enerji kullanımı; biyokütle, güneş, rüzgâr ve hidroelektrik gibi yenilenebilir enerji kaynaklarıyla fosil yakıtlara bağımlılığı azaltarak çevresel etkileri en aza indirir (Omer, 2008).

4. Geleneksel Tarım ve Bilgi Eksikliği

Geleneksel tarım uygulamaları, özellikle gelişmekte olan ve az gelişmiş bölgelerde hâlâ yaygın olup, çoğunlukla yüksek maliyet, sınırlı eğitim düzeyi ve pazarlama kanallarının kısıtlılığı gibi faktörlerden etkilenmektedir. Bu durum, çiftçilerin yeni tarımsal teknolojileri ve sürdürülebilir uygulamaları benimseme isteksizliğine yol açmaktadır. Üreticilerin bilgi eksikliği, sürdürülebilir tarım uygulamalarının verimli bir şekilde yayılmasının önünde önemli bir engel oluşturmaktadır; örneğin, uygulamaların maliyeti, faydaları ve doğru yöntemleri hakkında yeterli bilgiye sahip olmamaları, benimsemeyi geciktirmektedir (Pannell, 2008). Aynı zamanda, geleneksel tarım yöntemleri, iklim değişikliği, kuraklık, zararlılar ve doğal afetler gibi mevcut çevresel risklere karşı direnç geliştirmede sınırlı kalabilmektedir. Bu nedenle, üreticilerin bilgi ve eğitim düzeyinin artırılması, sosyal ağların güçlendirilmesi ve doğru yayım stratejilerinin uygulanması, sürdürülebilir tarımın etkin bir şekilde benimsenmesini ve uzun vadeli verimliliğin sağlanmasını mümkün kılmaktadır (Rogers, 2003; Ostrom, 1990).

5. İklim Değişikliği ve Sürdürülebilir Tarım

İklim değişikliği, küresel tarımın karşı karşıya olduğu en ciddi zorluklardan biri olarak ön plana çıkmaktadır. Artan sıcaklıklar, düzensiz yağış dağılımları, kuraklık, sel ve ekstrem hava olayları, tarımsal üretim üzerinde doğrudan ve dolaylı etkiler yaratmaktadır. Bu durum, çölleşme tehdidini artırmakta ve bazı bölgelerde tarımsal üretimi sürdürülemez hâle getirmektedir. Tuzluluk, böcek ve hastalık istilaları ile su kaynaklarının azalması hem bitkisel hem de hayvansal üretimi olumsuz etkilemektedir. Mevcut tarım alanlarının verimliliği, bu çevresel baskılar nedeniyle azalmakta, gıda güvenliği ve ekonomik sürdürülebilirlik üzerinde ciddi riskler oluşmaktadır. Küresel nüfusun 2050 yılına kadar 9,7 milyara ulaşması öngörülürken, bu etkiler tarım dışı kalacak alanların artması ve kaynakların daha verimli yönetilmesi ihtiyacını doğurmaktadır. Geleneksel tarım sistemleri, iklim değişikliğine uyum sağlama kapasitesi sınırlı olduğundan, sürdürülebilir tarım uygulamalarının önemi daha da belirginleşmektedir. Sürdürülebilir tarım, doğal kaynakların yönetimi ve korunmasını ön plana çıkararak iklim değişikliğinin olumsuz etkilerini azaltmayı hedefler (FAO). Toprak ve su döngülerinden, enerji akışlarından ve biyolojik çeşitlilikten maksimum yararlanmak hem verimliliği artırmak hem de çevresel zararları en aza indirmek açısından kritik öneme sahiptir. Örtü bitkileri, ürün ve peyzaj çeşitliliği, agroforestry, minimum toprak işleme ve organik gübreleme gibi uygulamalar, tarımsal sistemleri iklim stresine karşı daha dirençli hâle getirir. Bu yöntemler, aynı zamanda sera gazı emisyonlarının azaltılmasına, karbon bağlanmasına ve toprak sağlığının korunmasına katkı sağlar. İklim değişikliği ile mücadelede yenilikçi teknolojiler ve dijital tarım uygulamaları da önemli bir rol üstlenmektedir. Akıllı sulama sistemleri, hassas gübreleme ve yapay zekâ tabanlı üretim planlaması, tarımda kaynak kullanımını optimize ederek verimliliği artırmakta ve çevresel riskleri azaltmaktadır. Benzer şekilde, iklim dostu tarım uygulamaları, sera gazı emisyonlarını azaltan ve çiftçilerin iklim değişikliğine uyumunu kolaylaştıran stratejiler sunmaktadır. Bu yaklaşımlar hem ekonomik hem de ekolojik sürdürülebilirliği bir arada sağlayarak uzun vadeli üretkenliği güvence altına alır. Sürdürülebilir tarımın iklim değişikliği ile ilişkisi aynı zamanda sosyo-ekonomik boyutu da kapsamaktadır. Çiftçilerin eğitim düzeyi, bilgi eksikliği ve sınırlı erişim imkânları, yeniliklerin benimsenmesini sınırlandırmakta ve iklim risklerine karşı kırılganlığı artırmaktadır. Bu nedenle, bilgi ağlarının güçlendirilmesi, eğitim programlarının uygulanması ve topluluk temelli iş birliği mekanizmalarının desteklenmesi, iklim değişikliğine karşı daha dirençli ve sürdürülebilir tarım sistemlerinin oluşturulmasını mümkün kılmaktadır (Rogers, 2003; Ostrom, 1990).

6. Sürdürülebilir Tarım Yenilikleri ve Benimsenme Süreci

Sürdürülebilir tarım yenilikleri, iklim değişikliği, zararlılar, kuraklık, doğal afetler ve gıda güvensizliği gibi tarımın karşı karşıya olduğu zorlukların üstesinden gelmede önemli araçlar olarak kabul edilmektedir. Ancak bu yeniliklerin benimsenme düzeyi sınırlıdır ve benimsenmenin belirleyicileri üzerine daha fazla araştırmaya ihtiyaç duyulmaktadır. Bu durum, akademisyenlerin politika yapıcılara sürdürülebilir tarım yeniliklerinin benimsenmesini güçlendirecek daha net ve uygulanabilir mesajlar iletebilmesi için yeni çalışmaların gerekliliğini ortaya koymaktadır. Farklı kavramsal modeller; agroforestry sistemleri, gübre ağaç sistemleri, koruyucu tarım, organik tarım ve yeşil pestisitler gibi yeniliklerin benimsenmesini etkileyen faktörleri incelemektedir. Rogers tarafından geliştirilen "yeniliklerin yayılımı teorisi" (Diffusion of Innovations, DOI), yenilikçi teknolojilerin yayılımı ve benimsenmesinin; teknolojinin uyumluluğu ve karmaşıklığı, potansiyel kullanıcının özellikleri, kişinin teknolojiye ilişkin algısı ve bilgisi ile grup, kitle ve bireysel iletişim kanalları tarafından belirlendiğini öne sürmektedir. Tarımsal ürünlerde sürdürülebilir uygulamaların benimsenmesini etkileyen iki temel sosyal süreç bulunmaktadır. Bunlardan en bilineni, Rogers (2003) tarafından ortaya atılan ve tarımsal karar verme üzerine yüzlerce çalışmada uygulanan "yeniliğin yayılımı" modelidir (Prokopy ve ark., 2008). Bu hedeflere ulaşmak amacıyla birçok tarımsal ürün ve bölgede, üreticilerin sürdürülebilir uygulamaları benimsemesini teşvik eden yerel programlar ve ortaklıklar geliştirilmiştir (Warner, 2007a, b). Sürdürülebilir tarım, ekonomik, çevresel ve sosyal hedefleri birleştirmeyi amaçlayan bir yaklaşım olarak uzun bir geçmişe sahiptir (Hansen, 1996). Bu yaklaşım, tarımsal sistemlerin üretkenliğini ve faydasını uzun vadede sürdürebilmesini sağlayacak şekilde tasarlanmıştır (Ikerd, 1990). Sürdürülebilir uygulamaların benimsenmesi iki sosyal süreçle açıklanabilir: yenilik ve iş birliği. Ekonomik faydaların maliyetlerden fazla olduğu uygulamalarda yenilik, sosyal faydaların kolektif çabayla sağlandığı uygulamalarda ise iş birliği ön plana çıkar (Rogers, 2003; Ostrom, 1990). Sürdürülebilir yenilikler, çevresel ve sosyal fayda üretirken ekonomik değer sağlayan ürünler, hizmetler, teknolojiler, süreçler ve yönetim tekniklerini kapsar. Sürdürülebilir tarım yenilikleri; çiftçi düzeyinde yeşil gübre, kompost, koruyucu toprak işleme ve baklagil ekim nöbeti gibi uygulamaları; çiftlik dışı düzeyde ise kısa tedarik zincirleri ve kooperatiflerin benimsenmesini içerir. Ayrıca dijital tarım teknolojileri ve yapay zekâ çözümleri, su, gübre ve herbisit kullanımını optimize ederek değişen iklim koşullarına uyum sağlamayı desteklemektedir.

7. Yeni Araştırma Yönelimleri ve Teknolojik Uygulamalar

Ekolojik yoğunlaştırma, genetik ve sosyo-ekonomik yoğunlaştırma ile iklim dostu tarım gibi yeni araştırma yönelimleri, tarımsal verimliliği artırmayı ve çevresel etkileri azaltmayı hedeflemektedir. Bu yaklaşımlar, agroekoloji ve bütüncül sistem düşüncesi ile birleşerek, bitkiler, hayvanlar, insanlar ve çevre arasındaki karşılıklı bağımlılığı güçlendirmekte, gıda güvenliğini ve biyolojik çeşitliliği desteklemektedir. Sürdürülebilir tarımın, yalnızca bireysel üretim süreçlerini değil, aynı zamanda toplumsal yapıları, teknolojik yenilikleri ve politika mekanizmalarını da kapsayan kapsamlı bir sistem olduğu görülmektedir.

Sonuç

Sürdürülebilir tarımın etkin bir şekilde uygulanması, ekonomik, çevresel ve sosyal boyutların bir arada değerlendirilmesini gerektirmektedir. Ancak bu süreç, üreticilerin bilgi eksikliği, yüksek yatırım maliyetleri, yeniliğe isteksizlik, toplumsal farkındalık eksikliği ve karmaşık/yetersiz yasal çerçeveler gibi çok boyutlu sınırlamalarla karşı karşıyadır. Bu engeller, sürdürülebilir tarım uygulamalarının yaygınlaştırılmasını ve benimsenmesini güçleştirmektedir. Söz konusu sınırlamaların ekonomik, sosyal ve yönetsel boyutları, tarımın geleceğine yönelik stratejilerin yalnızca tek bir düzeyde değil, sektörler arası ve paydaşlar arası

iş birliğine dayalı olarak geliştirilmesini zorunlu kılmaktadır. Sürdürülebilir tarım, doğal kaynakların korunması, çevresel etkilerin azaltılması ve kırsal toplulukların yaşam kalitesinin iyileştirilmesi gibi hedefleri bütüncül bir şekilde ele alırken, teknolojik yeniliklerin ve dijital tarım çözümlerinin doğru uygulanmasıyla ekonomik sürdürülebilirliği de desteklemektedir. Günümüzde artan nüfus, iklim değişikliği ve doğal kaynakların azalması, tarımsal üretimde sürdürülebilirliği zorunlu hale getirmiştir. Bu bağlamda, sürdürülebilir tarımsal gelişmelerin hem yerel hem de küresel ölçekte değerlendirilmesi büyük önem taşımaktadır. Bu makalede sürdürülebilir tarım kavramını ve sistemlerini ele alarak; temel hedefleri, geleneksel tarımdaki bilgi eksikliklerini, iklim değişikliğiyle ilişkisini, yeniliklerin benimsenme sürecini, yeni araştırma yönelimlerini ve teknolojik uygulamaları incelenmiştir. Bu çalışma, mevcut tarımsal süreçler ve uygulamalara dair kapsamlı bir bakış sunmakta ve sürdürülebilir tarımın yayılımı ile etkinliğinin artırılması için odaklanılması gereken alanları ortaya koymaktadır. Özellikle bilgi ağlarının güçlendirilmesi, eğitim ve yayım programlarının geliştirilmesi, iklim değişikliği ve çevresel risklerin yönetilmesi ile yenilikçi teknolojilerin benimsenmesi, gelecekteki araştırmalar ve politika önerileri için kritik öneme sahiptir.

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ÖZET

Kuraklık, dünyada önemli çevre sorunlarından biridir. Bir mevsim ile birkaç yıl aralığı kapsayabilen, mevsim ortalamasından düşük yağış dönemleri ya da yağışın olmaması sonucu kuraklık ortaya çıkmaktadır. Bir bölgenin iklim koşulları temel alınarak, ilgili bölgede beklenen yağış miktarının düşmesi meteorolojik kuraklığı; belirli bir zaman aralığında, meralar ve üretimi yapılan belirli bir tarımsal ürün için gerekli olan toprak suyu ve toprak nemi olmaması tarımsal kuraklığı; yer altı ve yüzey suyu kaynaklarındaki azalma hidrolojik kuraklığı göstermektedir. Bu üç temel kuraklık türü ile doğrudan ya da dolaylı olarak ilişkili kuraklık türleri de bulunmaktadır. Bu kapsamda, hızlı bir şekilde başlayarak etkisi haftalarca sürebilen birçok sektörü olumsuz etkileyebilen kuraklık ani kuraklığı; ekosistemi etkileyen hem doğal hem de insan kaynaklı döngülere yol açan periyodik su kıtlığı ekolojik kuraklığı; su arzı ve talebine bağlı olarak endüstriyel hizmet ve ticari mal bulunabilirliğinin azalması sosyo-ekonomik kuraklığı temsil etmektedir. Kuraklık, doğal ve yapay nedenlerle meydana gelmektedir. Kuraklığın doğal nedenleri hava koşullarında değişkenlik, hava sirkülasyonu, okyanus sıcaklığında dalgalanmalar ve toprak neminin azalması olarak sıralanabilir. Kuraklığın yapay nedenleri ise tarımsal faaliyetlerin bilinçli yapılmaması, nehirler üzerine inşa edilen barajların kentleşme ve arazi değişikliklerine yol açabilmesi, ormanların yok olması ve madencilik faaliyetleri olarak sıralanabilir. Kuraklığın toprak ve su kaynaklarında bozulmalara bağlı olarak kaynaklarda tükenme, tarımsal üretim verimliliğinde düşme, biyolojik çeşitliliğin olumsuz etkilenmesi, kuraklık sonucu ormanların kuruması ve orman yangınları gibi etkileri bulunmaktadır. Dolayısıyla kuraklığın türleri, nedenleri ve etkilerine ilişkin bileşenler, kuraklıkla mücadele tedbirlerinin planlanması açısından önemlidir.

Anahtar Kelimeler: Çevre sorunu, Kuraklık, Kuraklık bileşenleri

TYPES OF DROUGHT, CAUSES AND EFFECTS

ABSTRACT

Drought is one of the major environmental problems in the world. It occurs as a result of periods of below-average rainfall or no rainfall at all, which can last from one season to several years. Based on a region's climatic conditions, a decrease in the expected amount of rainfall in that region indicates meteorological drought; the absence of soil water and soil moisture necessary for pastures and the production of specific agricultural products within a certain time frame indicates agricultural drought; and a decrease in groundwater and surface water resources indicates hydrological drought. There are also types of drought that are directly or indirectly related to these three basic types of drought. In this context, drought that begins rapidly and can last for weeks, negatively affecting many sectors, represents sudden drought; periodic water scarcity that causes both natural and human-induced cycles affecting the ecosystem represents ecological drought; and the decrease in the availability of industrial services and commercial goods depending on water supply and demand represents socio-economic drought. Drought occurs due to both natural and artificial causes. The natural causes of drought include variability in weather conditions, air circulation, fluctuations in ocean temperatures, and a decrease in soil moisture. The artificial causes of drought include the lack of awareness in agricultural activities, the construction of dams on rivers leading to urbanisation and land changes, deforestation, and mining activities. The effects of drought include depletion of resources due to degradation of soil and water resources, decline in agricultural production efficiency, negative impact on biological diversity, drying of forests as a result of drought, and forest fires. Therefore, the components related to the types, causes, and effects of drought are important for planning measures to address drought.

Keywords: Environmental problem, Drought, Drought components

1. Giriş

Dünya iklimlerinde meydana gelen kuraklık çevresel, ekonomik ve toplumsal etkileri olan bir doğal afet olarak kabul edilmektedir (Naumann vd., 2018; Van Loon, 2015). Kuraklığın başlangıcını tespit edebilmek, genel olarak zor olabilir. Kasırga, hortum ve deprem gibi ani gelişen birçok doğal afetin aksine, kuraklığın kademeli ve sinsi bir şekilde gelişebildiği rapor edilmiştir (Cravens vd., 2021; Wu vd., 2018a). Kuraklık, su döngüsünde aşırılık durumu ve diğer bağımlı sistemlerin zorladığı bir süreç olarak görülebilir (Wilhite vd., 2007). Dolayısıyla kuraklık, su döngüsünün herhangi bir noktasında, su talebi ve su arzı arasında dengesizliğe yol açan herhangi bir bağlantıda ortaya çıkabilir. Tarım ve enerji üretiminin su temini aşamasında aksamalar olması kuraklıkla ilişkili olup, kuraklık ekosistemler için önemli tehditlerden biridir. Tarımsal, endüstriyel ve yaşamsal alanlarda ihtiyaçlar su ile karşılanamadığında, olumsuz etkiler ortaya çıkabilir. Kuraklığın getirdiği olumsuzlukları en aza indirmek için su kaynaklarının planlanması ve yönetimi önem arz etmektedir. Su kaynaklarının tahsisi ve düzenlenmesi ile ilişkili olan kuraklık, su talebi ve su arzı bakımından değerlendirilebilir. Su temin sisteminde yüzey akışı, toprak nemi ve rezervuar suyu depolanması ile bitkilerin büyüme süreci su talep sisteminde bulunmaktadır. Su temini kapsamında, buzul ve yağış gibi su kaynaklarının zaman ve mekânsal ölçekte değiştiği bildirilmiştir. Geleneksel olarak bu durumların bir mevsim ya da daha fazla mevsim süresince kademeli gerçekleşmesi, kuraklık koşullarının yavaş şekilde başlaması ile karakterize edilmiştir (Jing vd., 2012; Fung vd., 2020; Mishra ve Singh, 2010). Kuraklığın olası etkilerinin yönetiminde ve buna uyum sağlamada, küresel ve bölgesel değerlendirmeler yapılması gerekmektedir. Bu derlemenin amacı, kuraklıkla mücadele tedbirlerinin iyi planlanması için kuraklığın türleri, nedenleri ve etkilerine ilişkin bileşenleri sunmaktır.

2. Kuraklık Türleri

Kuraklık genel olarak yağış, yer altı suyu, toprak suyu ve akarsu akışının dahil olduğu su eksikliği olarak tanımlanmıştır. Hidrolojik döngü değişkenleriyle ilişkili olan kuraklığın türleri bulunmaktadır. Bu türler Şekil 1'de sunulduğu üzere, temelde su eksikliğinin belirli değişkenlerine göre meteorolojik kuraklık, tarımsal kuraklık, hidrolojik kuraklık olarak sıralanabilir (Mishra ve Singh, 2010; NDMC, 2025). Bu temel kuraklık türleri ile ilişkili ani kuraklık, ekolojik kuraklık ve sosyo-ekonomik kuraklık türleri de bulunmaktadır (Mishra ve Singh, 2010).

2.1. Meteorolojik Kuraklık

Meteorolojik kuraklık, ardışık dönemlerde yağış azaldığında meydana gelmektedir. Bu kuraklık süresinin fazla olması, kanal akışı ve yer altı suyu rezervlerinde azalmayla hidrolojik kuraklığa neden olabilir. Toprakta mahsullere ulaşan su miktarı, tarımsal faaliyeti olumsuz etkileyecek ölçüde azaldığında tarımsal üretimde azalmaya yol açan tarımsal kuraklığı oluşturacaktır. Kuraklık yağış, sıcaklık, rüzgâr hızı ve güneşlenme süresi gibi faktörlerden etkilenmektedir. Bu faktörlere, antropojenik etkiler de eklendiğinde kuraklığın süreci belirsizlikleri beraberinde getirmektedir (West vd., 2019; Chang vd., 2024).

2.2. Tarımsal Kuraklık

Tarımsal kuraklık, toprak nem açığı ve yağış eksikliğinin yanı sıra hava sıcaklığı ve buharlaşma artışının sonucu olan toprak nem açığı olarak bildirilmiştir. Bu kuraklığın tarımsal faaliyet sonucu elde edilen ürünler üzerindeki etkisi mevsimlere göre değişkenlik göstererek, ürünlerin farklı büyüme adımlarıyla ilişkilendirilmiştir (Mishra ve Singh, 2010; Yu vd., 2018; Wu vd., 2018b).

2.3. Hidrolojik Kuraklık

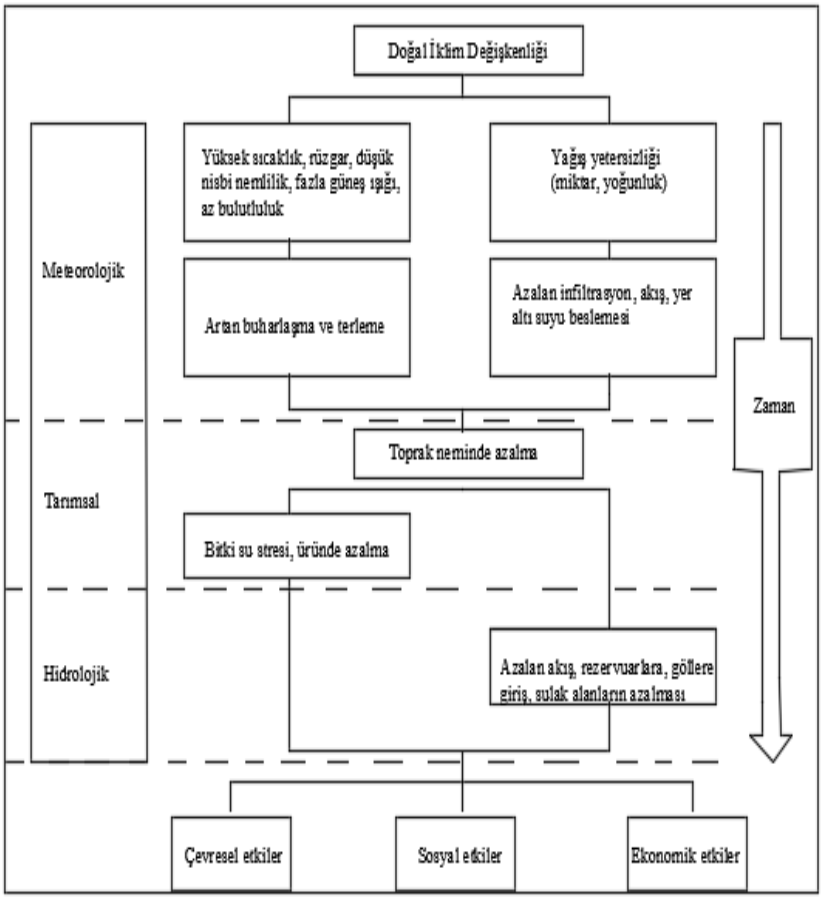
Meteorolojik kuraklığın genel olarak hidrolojik kuraklığın kaynağı olduğu rapor edilmiştir. Atmosferik süreçlerde meydana gelen anormal durumlar veya antropojenik etkiler nedeniyle yüzey suyu, yeraltı suyu veya rezervuar seviyelerinin uzun vadeli ortalamaların altına düşmesi sonucu hidrolojik kuraklık meydana gelmektedir. Bu kuraklık, tarımsal, evsel ve endüstriyel sistemlerde su arzını tehdit edebilir. Bu nedenle hidrolojik kuraklığın gelişim süreci, kuraklık risk yönetimi ve su kaynakları yönetimi için önem arz etmektedir (Wang vd., 2016; Zhang vd., 2022).

2.4. Ani Kuraklık

Ani kuraklık, yağışın hızla azalmasının neden olduğu buharlaşmadaki artış ve toprak nemliliğinin ani kuruması olarak bildirilmiştir (Koster vd., 2019; Osman vd., 2022). Yağışın ani düşüşü genel olarak normal olmayan derecede yüksek sıcaklık ya da sıcak hava dalgası, güneş radyasyonu, rüzgâr ve düşük nem seviyesini beraberinde getirmektedir (Lowman vd., 2023).

2.5. Ekolojik Kuraklık

Ekolojik kuraklık ekosistemleri dayanıklılık eşiğinin ötesine, savunmasız duruma getiren, ekosistem hizmetlerini etkileyen su mevcudiyetinde epizodik bir açıklık olarak bildirilmiştir (Crausbay vd., 2017). Ekolojik hassasiyetli bölgelerde, büyüme hızı ve hidrolojik süreçleri değiştirmek gibi çeşitli değişiklikler nedeniyle nem ve termal koşullar bitki örtüsü sağlığını etkilemektedir (Vose vd., 2016; Clark vd., 2016).



Şekil 1. Kuraklık türleri

2.6. Sosyo-Ekonomik Kuraklık

Su kaynaklarının su talebini karşılayamadığı durumlarda ortaya çıkan kuraklık türüdür (Zhao vd., 2019). Dolayısıyla, su arzı ve talebiyle ilişkilendirilmektedir.

3. Kuraklık Nedenleri

Atmosfer sistemindeki nem, dünya okyanuslarından kıtalara taşınmaktadır. Bu nemin bir kısmı yeraltı su katmanları, göller ve buzullara hapsolmakta ve nemin geri kalan kısmı ise bitki, nehir ve toprak aracılığıyla akmaktadır. Dolayısıyla kuraklık, genel olarak nem akışındaki sapmalar nedeniyle oluşmaktadır (Ault, 2020). Kuraklığın doğrudan nedenini belirlemek karmaşık olup, genel olarak yağış olmaması veya yağış seviyesinin ortalamanın altında olması durumunda meydana geldiği bilinmektedir. Ayrıca su kaynaklarının kötü yönetimi, ormansızlaşma, arazi kullanımı ve madencilik faaliyetleri gibi antropojenik etkilerin kuraklığın sıklığı ve şiddetini kolayca arttırabileceği bilinmektedir (Ayugi vd., 2020; Abara vd., 2020).

Hava koşulları değişkenliği, hava sirkülasyonu, toprak neminde azalma, okyanus sıcaklığında dalgalanma gibi faktörler, doğal faktörler kaynaklı kuraklıktır. Dünyada bazı bölgelerde, iklim değişikliğine bağlı olarak sıcaklık artışı ve buharlaşma artışı, yaşam koşullarını zor duruma getirmektedir. Buna ilaveten, bazı bölgelerde de yağışın azalması kuraklık riskini arttırmaktadır (Ndayiragije ve Li, 2022).

Su döngüsünün mekânsal düzeni ve sürecini baraj inşaatı, çok havzalı su transferi, tarımsal su yönlendirme ve yapay yağmur gibi insan faaliyetleri, bölgesel buharlaşma taşınım sürecini dönüştürebilir ve su dengesini değiştirebilir. Bu faaliyetlerin su miktarı ve kalitesinin zamansal ve mekânsal süreçlerini değiştirdiği bildirilmiştir. Su talebi sisteminde hidrolik düzenleme kapasitesi, tarımsal yapı, endüstriyel yapı, nüfus gelişimi gibi durumlar, su döngüsü sisteminde su talebini değiştirebilir (Jing vd., 2012).

4. Kuraklık Etkileri

İklim değişikliği etkilerinin çok yönlü olması göz önünde bulundurulduğunda kuraklığın süre, yoğunluk ve alansal yayılım bakımından hem bölgesel değişiklik hem de yerel değişiklik gösterdiği rapor edilmiştir (Loukas vd., 2008). Su temini, yağış ve sıcaklığa duyarlıdır. İklim değişikliğine bağlı olarak topraktaki değişim ve bitki örtüsü, buharlaşma oranını değiştirebilir. Bu değişiklik nedeniyle, su döngüsünde değişimlerin sonucu olarak hidrotermal dengenin bozulacağı beklenmektedir. Kuraklık yüzey sularında azalma, akış hızlarında değişme ve artan şekilde çok yıllık ve çok yıllık olmayan alanların kısmen ya da tamamen kuruması şeklinde kendini göstermektedir. Dolayısıyla balıklar, algler, bitkiler ve mikroorganizmaların dahil olduğu tatlı su ekosistemlerinin taksonomik ve işlevsel biyoçeşitliliğinde azalmalara yol açarak ekolojik süreçleri ve insanlara sağladığı avantajları değiştirmektedir. Kuraklık sıklığı, sıcaklık artışı ile ilişkilendirilerek su kaynağı sisteminin kararlılığını azaltmaktadır. İklim değişikliğinin enerji süreci ve dinamik alanı değiştirerek sıcaklık, yağış ve rüzgâr faktörünü değiştirdiği bildirilmiştir. Buna ilaveten, hava olaylarının aşırılığı arttıkça toprak nemi, yer altı suyu, yüzey suyu ve diğer su kaynaklarının yapısının değişebileceği rapor edilmiştir (Jing vd., 2012; Stubbington vd., 2024).

5. Sonuç

Gelecekte olası kuraklıklara uyum sağlamak ve yönetmek için kuraklığın türleri, nedenleri ve etkilerine ilişkin bileşenlerin, yeni bilgi ve tekniklerin uygulanması açısından değerlendirilmesi gerekmektedir. Kuraklığın nasıl geliştiği anlaşıldığında, kuraklık etkileri azaltılarak gıda güvenliği ve sürdürülebilir bölgesel kalkınma sağlanabilir. Böylece, küresel ve belirli bir alandaki kuraklık davranışının anlaşılmasında ilerleme kaydedilmesi kaçınılmaz olacaktır.

Doğa ve insan arasında geri beslemeleri kapsayan bileşik süreçlerle karakterize edilen çok boyutlu ve ölçekli bir olgu olarak kuraklığın anlaşılması, su kaynakları sistemlerinin yönetimi ve planlanması için avantajlı olacak yeni bakış açıları sağlayacaktır. Doğal akış rejimlerini destekleyen ve habitatlarda çeşitlendirme yapan doğal süreçlere teşvik eden yönetim stratejileri, işlevsel olarak ekosistemlerde biyoçeşitliliği desteklemek için hayati önem taşımaktadır. Kuraklığa ilişkin durumları iyi yönetebilmek için hem küresel hem de bölgesel iş birlikleri yapılması önerilmektedir.

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DİJİTAL TARIMIN ÇİFTÇİ DAVRANIŞLARI VE TARIMSAL POLİTİKALAR ÜZERİNDEKİ ETKİLERİ

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ÖZET

Bu çalışmada dijital tarımın çiftçi davranışları ve tarımsal politikalar üzerindeki etkileri incelenmiştir. Öncelikle dünyada ve Türkiye'de dijital tarımın gelişimi ele alınmış, kullanılan teknolojiler ve uygulama örnekleri kısaca değerlendirilmiştir. Çalışmanın bulguları, dijital tarımın çiftçilerin üretim kararlarını daha bilinçli ve planlı hâle getirdiğini göstermektedir. Ayrıca verimlilik, kaynak kullanımı ve risk yönetimi gibi konularda olumlu etkiler sağladığı görülmüştür. Türkiye'de dijital tarım uygulamaları giderek artmakla birlikte, altyapı ve dijital okuryazarlık gibi bazı sınırlamalar sürecin hızını etkileyebilmektedir. Araştırma ayrıca, dijitalleşmenin tarımsal politikaların veri temelli ve daha hedef odaklı olmasına katkı sağladığını ortaya koymaktadır. Genel olarak çalışma, dijital tarımın hem üreticiler hem de tarım politikaları için önemli bir dönüştürücü güç olduğunu göstermektedir.

Anahtar Kelimeler: Tekonoloji, gelişme, tepki,etki, davranış,dijital tarım

IMPACT OF DIGITAL FARMING ON FARMER BEHAVIOR AND AGRICULTURAL POLICIES

ABSTRACT

This study examines the impact of digital agriculture on farmer behavior and agricultural policies. First, the development of digital agriculture globally and in Turkey is examined, and the technologies and application examples used are briefly evaluated. The study's findings indicate that digital agriculture enables farmers to make more informed and planned production decisions. It has also been shown to have positive impacts on productivity, resource utilization, and risk management. While digital agriculture applications are steadily increasing in Turkey, some limitations, such as infrastructure and digital literacy, can slow the pace of the process. The study also reveals that digitalization contributes to agricultural policies being data-driven and more targeted. Overall, the study demonstrates that digital agriculture is a significant transformative force for both producers and agricultural policies.

Keywords: Technology, development, reaction, impact, behavior, digital agriculture

GİRİŞ

Dijital tarım, sensörler, modüller ve dronlar gibi teknolojik aletlerle ekim yapılacak tarlaya özel havadan ve sudan aldığı verileri analiz ederek ekim ve hasat zamanlarını tarımsal süreci, hava durumunu, maliyeti ve erken uyarı sistemi hakkında genel bilgileri çiftçiye sunan bir sistemdir. Dünya genelinde tarımsal üretim; iklim değişikliği, nüfus artışı, girdi maliyetlerindeki yükselme ve iş gücündeki azalma gibi önemli baskılarla karşı karşıyadır. Bu nedenle, tarım sektöründe dijital teknolojilerin kullanımı hızla artmakta ve Tarım 4.0 olarak adlandırılan yeni bir paradigma ortaya çıkmaktadır. Dijital tarım; sensör teknolojileri, uydu görüntüleri, dronler, nesnelerin interneti (IoT), büyük veri analitiği, yapay zeka ve robotik sistemlerin tarımsal üretim süreçlerine entegre edilmesini kapsamaktadır. Dijital tarım gıda sektörünü önemli ölçüde geliştirme potansiyeline sahip olup geleceğin en önemli faktörlerinden biri haline gelmektedir. ileri teknolojiyi insanların kontrolünde çok yönlü bir sistem haline getirmeyi amaçlamaktadır. Dijital tarımın sağladığı dijitalleşme tarımın daha ekonomik ve devamlı olması için önemli bir etken iken aynı zamanda gıda güvenliği ve çevre için de çok önemlidir. Bilimsel araştırmalar, dijital tarım teknolojilerinin başarılı olabilmesi için çiftçilerin bu teknolojileri benimsemesi gerektiğini, bunun da eğitim ve bilinçlendirme programlarıyla desteklenmesi gerektiğini göstermektedir. Tarım sektörü insanlık tarihinin en önemli geçim kaynağı olmuş ve zaman ilerledikçe yenilikler ve değişiklikler yaşanmıştır. Türkiye tarım ekonomisi anlamında dünyada önemli bir yere sahiptir ayrıca sahip olduğu tarımsal alan, genç nüfus yoğunluğu ve Avrupa Asya gibi pazarlara yakınlığından dolayı büyük bir potansiyele sahiptir. Teknolojik gelişmelerden ve dijital tarımdan yararlanılırsa sahip olunan bu tarım potansiyelinden en üst seviyede yararlanabilecektir. Türkiye gibi gelişmekte olan ülkeler nüfusun belli bir kısmının tarım sektöründe çalışması, teknolojik yetersizlik tarım üretiminin büyük ölçüde doğal şartlara bağlı olması ayrıca organizasyon eksikliği gibi konuların çözüme kavuşması için altyapı ve teknolojiye yatırım yapılması gerekmektedir. Bu çalışmanın amacı, teknolojinin gelişmesiyle beraber tarım politikalarının ve çiftçilerin bu yenilik ve gelişmeler üzerindeki tepkileri ve davranışlarını gözlemlemektir. Araştırma, Türkiye tarımının dönüşüm potansiyeli ve politika yapıcılar için stratejik çıkarımlar sunması açısından önem taşımaktadır.

1.GELENEKSEL TARIMDAN DİJİTAL TARIMA

Tarım sektörü geleneksel yöntemlerden tarım teknolojilerine doğru bir kayma yaşamaktadır. Geleneksel tarımda büyük çoğunlukla insan gücünden yararlanılırken dijital tarımda sensörler, dronlar, modüller gibi sistemlerden yararlanılmaktadır. Dijital tarımda kullanılan modern teknoloji daha verimli ve daha sürdürülebilir bir üretim süreci sunmaktadır. Aşağıdaki tabloda, bu iki tarım türünün temel farklılıkları karşılaştırmalı olarak ele alınmaktadır.

Sanayi Devrimi ile Tarım 1.0 dönemini başlanmıştır. 1950'lerde yaşanan Yeşil Devrim, seri üretim teknikleri ve traktör kullanımının yaygınlaşmasıyla verimliliği artırırken; 1990'lardan itibaren bilgisayar ve otomasyon sistemleriyle hassas tarım uygulamaları devreye girmiştir. Günümüzde ise Tarım 4.0 olarak adlandırılan dijital tarım dönemi, bilgi ve teknolojilerinin, yapay zeka, büyük veri ve nesnelerin interneti gibi yenilikçi sistemlerle birleşerek tarımı daha verimli, sürdürülebilir ve akıllı hâle getirmesini sağlamaktadır.

Tablo 1. Geleneksel Tarım ve Dijital Tarım Arasındaki Farklar

ÖZELLİKLER	GELENEKSEL TARIM	DİJİTAL TARIM
İş Gücü ve İhtiyacı	Yoğun iş gücü gerektirir.	Geliştirilen robotik cihazlar ve dronlar sayesinde daha az iş gücü ile yapılır.
Üretim Süreci ve Verim	Ürün elde etme süreci uzundur ve bunun sonucu olarak üretim miktarı da düşüktür.	Daha kısa sürede ürün yetiştirilebilmektedir. Buna bağlı üretim oranı yüksektir.
Hastalık ve Zararlar	Bitki hastalık ve zararları geç tespit edilmektedir bunun sonucunda geç müdahale edilmektedir.	Bitki hastalıkları daha erken tespit edilmektedir.
Tahmin ve Analiz	Arazi durumu, ürün ve verim hakkında tahmin yürütülmektedir.	Büyük oranda hassasiyet ve doğrulukla sonuca varılmaktadır.
Sulama Bağımlılığı	Çiftçiler, sulama için tüp kuyulara sahip oldukları için muson yağmurlarına bağımlı değillerdir.	Akıllı sulama sistemleri ile su tasarrufu sağlanır.
Girdi Kullanımı ve Verimlilik	Aşırı girdi kullanımı vardır ve düşük verimliliğe sahiptir.	Modern tarımda girdiler daha düşüktür.
Üretim Süresi ve Bilimsellik	Bu teknikler çok zaman alır ve üretim azdır.	Zamandan tasarruf sağlanır ve bilime dayalı üretim yapılır
Uygulama Tarihi	Geleneksel tarım uygulamaları, geçmişi çok eskilere dayanan ve artık uygulanmayan uygulamalardır.	Modern tarım tamamen sermaye yoğunluğuna dayalıdır.
Gübre Kullanımı	Gübre olarak inek gübresi ve diğer doğal gübre türleri kullanılır.	Pestisitler ve kimyasal gübreler kullanılmaktadır.
Tohum Kullanımı	Kullanılan geleneksel tohumlar vardır.	Modern tarımda genetik olarak geliştirilmiş tohumlar tercih edilebilir.

(Çilesiz ve Karaköy, 2022).

1.1 Dijital Tarım Teknolojileri ve Uygulama Alanları: Dijital tarım, tarımsal üretimde ölçülebilirliği, izlenebilirliği ve verimliliği artıran teknolojilerin geniş bir yelpazesini içermektedir. Bu teknolojiler arasında:

Hassas Tarım Uygulamaları: Sensörler, uydular ve dronlar ile bitki sağlığı, besin durumu ve toprak nemi gibi özellikleri izlenerek su, ilaç ve gübre kullanımı optimize edilmektedir. Ayrıca hassas tarım ilaç kullanımını azaltmayı, hayvanların potansiyelinden en üst düzeyde faydalanmayı ve hastalıkları erken teşhis etmeyi sağlamaktadır. Geleneksel sağım sistemleri veri depolayamazken, tasarlanan sistem sağım sırasında ölçülen verileri mikrodenetleyici ile Raspberry Pi'a kablosuz aktarılmaktadır. Veriler MySQL veri tabanında saklanır ve Android cihazlardan erişilmektedir. Süt miktarı ve sıcaklığı anlık izlenebilir, tarihe göre filtrelenerek analiz edilebilmektedir. Toplanan bilgiler PDF olarak raporlanabilir; böylece sağım süreci takip edilerek hayvan sağlığı ve verimliliğine yönelik veri temelli kararlar alınabilmektedir.

IoT Tabanlı Sistemler: Tarla ve sera ortamında sıcaklık, nem, EC, pH ve ışık gibi parametreler gerçek zamanlı ölçülerek otomatik kontrol sağlanmaktadır. IoT (Nesnelerin İnterneti) tabanlı sistemler, sensörler ve internet bağlantısı aracılığıyla verilerin toplanmasını, iletilmesini ve analiz edilmesini mümkün kılmaktadır. Bu sistemler, toprak nemi, sıcaklık, ışık, pH, hava durumu ve bitki sağlığı gibi parametreleri izleyerek veri odaklı karar alınmasını sağlamaktadır. IoT çözümleri sulama, gübreleme ve ilaçlama süreçlerini otomatikleştirerek kaynak kullanımını optimize emektedir. Ayrıca hayvan sağlığı takibi, sera koşullarının kontrolü ve ürün

izlenebilirliği gibi uygulamaları da desteklemektedir. Böylece üretim verimliliği artarken maliyetler düşer ve çevresel etkiler azalır (Akpınar, 2025).

Yapay Zeka ve Büyük Veri Analitiği: Büyük veri, tarımda üretim tahmini, hastalık riski analizi ve doğru uygulama zamanlarını belirler. Bu teknoloji, doğal dil işleme, görüntü tanıma ve öngörücü analizler gibi birçok alanda (Russell ve Norvig, 1995) tercih edilip kullanılabilmektedir. Yapay zeka ve Nesnelerin İnterneti, verileri kullanarak ürün kalitesini artırır, süreçleri optimize ederek maliyet ve israfı azaltmaktadır. Endüstri 5.0 ile tarım, uzaktan algılama, yapay zeka ve bulut bilişimle dönüşmektedir. Büyük Veri Analitiği, hava, toprak, sulama, uydu ve pazar verilerini işleyerek verim tahmini, risk analizi ve kaynak optimizasyonu sağlamaktadır. Böylece çiftçiler daha hızlı, doğru ve sürdürülebilir kararlar alabilmektedir (Akpınar 2025; Çakmakçı ve Çakmakçı, 2023; Dertli ve Dertli, 2023).

Robotik Sistemler ve Otomasyon: Otonom traktörler, robotik hasat makineleri ve otomatik sulama sistemleri iş gücü verimliliğini artırmaktadır. Dijital tarımda robotik sistemler ve otomasyon, ekim, sulama, gübreleme, ilaçlama, hasat ve paketleme gibi tekrarlayan işleri insan müdahalesi olmadan yürütülmektedir. Bu teknolojiler iş gücü maliyetlerini düşürür, üretimde hassasiyeti artırır ve kaynak kullanımını optimize eder. RPA, işletmelerin verimliliğini artırırken, hata oranlarını düşürerek maliyet avantajı sağlama konusunda da büyük etkiler yaratabilmektedir. Özellikle finans, insan kaynakları ve müşteri hizmetleri gibi alanlarda yaygın olarak kullanıldığı (Aguirre ve Rodriguez, 2017) göz önüne alındığında çok kapsamlı bir perspektif çizmektedir. RPA yazılımları, büyük veri ve yapay zeka ile birleştirildiğinde, süreçlerin daha akıllı hale gelmesine olanak tanımaktadır (Akpınar, 2025).

Dijital Pazarlama ve Blok Zincir: Ürün izlenebilirliği, kalite sertifikasyonu ve aracısız satış mekanizmaları dijital tarım ile güçlenmektedir. Dijital pazarlama, çiftçilerin ürünlerini online platformlar ve sosyal medya üzerinden doğrudan tüketici veya perakendeciye sunmasını sağlayarak pazar erişimini artırmaktadır. Blok zincir teknolojisi, tedarik zincirinde veri doğruluğunu garanti eder, ürünlerin menşei, işlenme ve dağıtım süreçlerini kaydederek gıda güvenliği ve izlenebilirlik sağlayarak sahtecilik ve hatalı bilgilerin önüne geçmektedir. Ayrıca blok zincir, ödeme ve sözleşme süreçlerini otomatikleştirerek çiftçilerin gelirlerini güvence altına alır ve veri temelli üretim kararlarını desteklemektedir (Çakıroğlu, 2023).

2.TEKNOLOJİ ADAPTASYONU VE DİJİTAL OKURYAZARLIK

Tarımsal alanda başlıca zorluklar arasında kırsal alanda altyapı eksikliği, dijital okuryazarlık düzeyinin düşük olması ve yüksek maliyetler bulunmaktadır. Dijital tarıma adım atmak için ilk olarak dijital altyapının oluşturulması gerekmektedir. İşletmeye uygun bir dijital altyapı planı oluşturulmalı ve çalışanlara da gerekli olan dijital teknoloji eğitimi verilmesi yeni teknolojilerin anlaşılmasına ve kullanılmasına katkı sağlayacaktır. Örneğin, Pakistan'da yapılan bir çalışmada dijital eğitimler, enerji verimli tarım uygulamalarının benimsenmesini ve çiftçilerin refahını arttırmıştır. Benzer şekilde, Kenya'da küçük ölçekli çiftçiler yapay zeka destekli araçlar sayesinde üretkenliklerini artırmış, ancak alt yapı ve dijital okur yazarlık eksiklikleri benimsemeyi sınırlamıştır. Bu nedenle, eğitim, uygun alt yapı ve devlet destekleri, dijital tarımın yaygınlaşması ve sürdürülebilir şekilde uygulanması için kritik önemdedir. Ayrıca, AB ve diğer ülkelerdeki dijital tarım politikaları, çiftçilerin teknolojiyi daha etkin kullanabilmesi ve tarımda sürdürülebilirliğin sağlanması açısından örnek teşkil etmektedir. Dijital tarım sadece üretim de verimliliği artırmakla kalmaz, aynı zamanda çevresel kaynakların korunmasına ve ekonomik sürdürülebilirliğe de katkı sağlar. Karar verici konumdaki üreticilerin yaş ortalaması 50-55 yaş civarındadır. Yaş ile eğitim durumu açısından teknoloji kullanımın düşük olması, teknolojik yeniliğin ezberleri bozması ya da teknolojik dönüşümlerden kaçınılması tarım sektöründe dijitalleşmenin önündeki en önemli engel olarak

görülmektedir. Tarım alanın da kullanılan teknolojik ekipman ve yazılım teknolojilerinin birbiri ile uyumu ekipmanların birlikte çalışabilirliği için çok önemlidir. Modern teknolojilerin, geleneksel teknolojilere göre daha maliyetli olması çiftçilerin bu teknolojiden yararlanmasının önüne geçmektedir. Tarımsal dijitalleşme iklim değişikleri ile mücadelede önemli bir faktördür. Tarım sektörünün dijitalleşmesi için öncelikle karşılaştığı zorlukların ortadan kaldırılması gerekmektedir. Zorlukların aşılması için devlet ve özel sektör ortaklaşa çalışarak, kırsal alanlarda altyapının geliştirilmesi, dijital okuryazarlık düzeyinin yükseltilmesi, dijital teknolojilerin maliyetinin düşürülmesi gerekmektedir. Aşağıdaki tabloda zorluklar, zorlukların detayları ve çözüm stratejileri önerilmiştir (Akpınar, 2025; Göl ve Tarhan 2024; Tutar ve ark. 2025).

Zorluklar	Zorlukların Detayları	Çözüm Stratejileri
Dijital Altyapı Eksikliği	Kırsal alanda teknolojik ve internet altyapı yetersizliği. ve enerji altyapısı sorunları teknolojinin yaygınlaşmasını sınırlamaktadır	Devlet ve özel sektör dayanışması ile kırsal alanlara altyapı desteği.
Dijital Okuryazarlık Düzeyinin Düşüklüğü	Çiftçilerin teknolojiye karşı uyum sağlama güçlüğü, yaş ve eğitime bağlı olarak teknolojiden kaçınma.	Çiftçiler için dijital becerilerinin artırmaya yönelik eğitim programlarının düzenlenmesi.
Yüksek Maliyetler	Dijital teknolojilerin yüksek maliyeti çiftçilerin erişimini engelliyor.	Çiftçilerin erişimi için ölçeklenebilir ve uygun maliyetli çözümlerin geliştirilmesi.
Veri Güvenliği ve Gizliliği	Büyük miktarda verinin toplanması ve işlenmesi Hassas tarım verilerinin korunması.	Güçlü şifreleme yöntemleri, güncel güvenlik protokollerine uyulması ve siber tehditlere karşı önlemler alınması.
Teknik Uyum ve Standardizasyon	Farklı teknolojik ekipmanların birlikte çalışabilirliği, teknik problemlere karşı çiftçilerin yetersiz kalması.	Tarım teknolojilerinde standardizasyonun teşvik edilmesi. Çiftçilerin sorunlara karşı destek alabilecekleri sistemlerin oluşturulması.
Kültürel ve Sosyal Engeller	Yaşlı çiftçilerin teknolojiye adaptasyonunda zorluklar. Dijital dönüşümün benimsenmesinde direnç.	Dijital dönüşümün faydalarını gösteren örnekler, pozitif algı yapmak için kampanyalar.
İklim Değişikliği ile Mücadele	İklim değişikliğine karşı tarım sektörünün direncini artırmak için dijitalleşmenin zorlukları.	Dijitalleşmenin iklim değişikliğiyle mücadelede nasıl kullanılacağını araştıran politikaların desteklenmesi

(Göl ve Tarhan, 2023).

2.1. Risk Yönetimi ve Sigorta Davranışı: Dijital veriler, hastalık, kuraklık ve don gibi riskleri erken tespit ederek çiftçilerin sigorta talebi ve risk yönetimini geliştirir. Tarım, doğal ve ekonomik risklerden en çok etkilenen sektördür; gelişmiş ülkeler tarım sigortası ve risk yönetim programları ile verim ve gelir kayıplarını çiftçiden sigorta sistemlerine transfer etmektedir. Tarımsal üretimde dolu, don, yangın, kuraklık, fırtına ve sel başlıca risklerdir (Tesbi, 2000). Çiftçiler yağmurlama, sisleme, örtü ve rüzgâr pervaneleri gibi önlemler alır; ekonomik zararlar ise ürün sigortası ile ilgili kuruluşlara transfer edilmektedir. Tarım sigortası, üretimin sürekliliği ve çiftçi gelirlerinin istikrarı için gerekli bir risk yönetimi aracıdır; kapsam ve yöntemi, ürünlerin doğal risklere duyarlılığı, risk sıklığı, hasar miktarı ve tarımın ekonomik önemi dikkate alınarak belirlenir (Çetin, 2003; Akçaöz ve ark., 2006).

3.2. Pazarlama Davranışları ve Dijital Platform Kullanımı: Dijital pazar uygulamaları, çiftçilerin ürünlerini avantajlı satmasını sağlayarak pazarda güç kazandırmaktadır. Dijital

okuryazarlık; dijital araçları kullanma, bilgiye erişme, değerlendirme, üretme ve paylaşma becerilerini kapsamaktadır (Bawden, 2008; Rainie ve ark., 2012).

3.3. Dijital Tarımın Tarımsal Politikalar Üzerindeki Etkileri: Dijitalleşme tarım politikalarını dönüştürmekte, verimlilik ve çiftçi refahını artırırken maliyetleri düşürmektedir. Türkiye'de yüksek maliyetler, altyapı ve personel yetersizlikleri ile dışa bağımlılık gelişimi sınırlamaktadır. Tarımsal örgütlenme, destekler, yerli Ar-Ge ve bağımlılığı azaltacak politikalar bu sorunları çözerek dijital tarımı sürdürülebilir üretim ve kırsal kalkınmada stratejik kılmaktadır (Yılmazer ve Tunalıoğlu, 2024).

3.4. Veri Temelli Politika Geliştirme: Dijital tarım verileri, tarım politikalarının hızlı, doğru ve yerelleştirilmiş şekilde oluşturulmasını sağlamaktadır. Değişken oranlı uygulama ve verim izleme sistemleri, tarla içi farklılıkları yönetmeyi kolaylaştırmaktadır. Yapay zeka, makine öğrenmesi ve IoT uygulamaları karar destek sistemlerini güçlendirmektedir. Değişken oranlı uygulama ve verim izleme sistemleri, Yapay zeka, makine öğrenmesi ve IoT uygulamalarının birlikte kullanımı çiftçilerin doğru zamanda doğru müdahale yapmasını sağlamaktadır. Dijital görüntü işleme teknikleri, ürün kalitesinin takibi ve zararlı hastalıkların erken teşhisi ile tarımsal sürdürülebilirliği desteklemektedir. Sensörler, uydu görüntüleri, dron ve iklim verileri analiz edilerek riskler öngörülür, üretim planlaması optimize edilir ve destekleme modelleri hedef odaklı hâle gelir. Böylece veri temelli politikalar, iklim uyumu ve gıda güvenliğini destekleyerek daha dirençli bir tarım sistemi oluşturmaktadır (Kılavuz ve Erdem, 2019; Severoğlu, 2025).

3.5. Destekleme Politikalarının Dijitalleşmesi: Veri tabanlı destekler, performans ve çevresel katkı odaklı teşvikler ile karbon ayak izi bazlı destekler dijital tarımda önem kazanmaktadır. Türkiye'de Kırsal Kalkınma Yatırımlarının Desteklenmesi Programı (KKYDP) ve AB destekli Tarım ve Kırsal Kalkınma Programı (IPARD), çiftçiler ve tarımsal küçük ve orta ölçekli işletmeler (KOBİ) için finansman sağlamaktadır. KKYDP, Türkiye'de ulusal kaynaklarla yürütülen kırsal kalkınma amaçlı tarımsal destekleri kapsamaktadır. Türkiye, Avrupa Birliği ve dünya genelinde tarım ve kırsal kalkınma desteklerinin etkinliğini artırmak için izleme ve değerlendirme çalışmalarına önem verilmektedir. Dünya Bankası, Avrupa Komisyonu ve OXFAM gibi kurumlar, son 20-30 yıldır proje kılavuzlarının hazırlanmasında çok yönlü metodoloji ve yaklaşımların geliştirilmesini desteklemektedir. Sübvansiyonlu krediler de dijital tarım yatırımlarına erişimi kolaylaştırmaktadır (Ataseven ve ark., 2020; Çobanoğlu ve ark. 2017).

3.6. İzlenebilirlik ve Gıda Güvenliği Politikaları: Blok zincir ve dijital kayıt sistemleri, ürünlerin izlenebilirliğini artırarak gıda güvenliğini desteklemektedir. Karar Destek Sistemleri (KDS), toplanan verilerin analiz edilerek kullanıcıya anlamlı bilgi sunulmasını sağlamaktadır. Bu sistem, tarımsal verileri işleyerek çiftçilere sulama zamanlaması, gübre kullanımı ve hastalık yönetimi gibi konularda önerilerde bulunabilecek bir yapıya sahiptir. Sürdürülebilir tarım, doğal kaynakları koruyarak, çevreyi kirletmemekte ve biyolojik çeşitliliği sürdürmektedir. Böylece kimyasal girdilerin azaltılması ve çevre dostu teknolojilerle uzun vadeli sağlıklı ve güvenilir gıda üretimini sağlamaktadır.

3.7. Çevresel Sürdürülebilirlik ve İklim Politikaları: Dijital tarım, su tasarrufu, gübre ve karbon emisyonlarının azaltılmasıyla ulusal iklim stratejilerine katkı sağlamaktadır. 2050'de artacak nüfus ve FAO'ya göre %60 artırılması gereken tarımsal üretim, hızlı bir dönüşümü zorunlu kılmaktadır. İklim-Akıllı Tarım, üretkenliği artırırken iklim uyumunu ve karbon tutumunu güçlendirmektedir. İklim değişikliği, tarımsal üretimi ve gıda güvenliğini ciddi şekilde tehdit etmektedir. Zararlı organizmaların artması ve çevresel koşulların değişmesi, gıda

arzını riske atmaktadır. Bu nedenle ülkeler, doğal kaynakları koruyan ve çevreye zarar vermeyen sürdürülebilir tarım uygulamalarına yönelmek zorundadır (Karaman, 2024).

SONUÇ

Bu çalışmada dijital tarımın dünyada ve Türkiye'deki genel durumu incelenmiş, ardından bu teknolojilerin çiftçi davranışları ile tarımsal politikalar üzerindeki etkileri değerlendirilmiştir. Bulgular, dijitalleşmenin küresel ölçekte tarımın dönüşümünde belirleyici bir rol oynadığını göstermektedir. Dünya genelinde sensör teknolojileri, uydu verileri, yapay zeka destekli tahmin modelleri ve otomasyon sistemlerinin tarımsal üretimde yaygınlaştığı görülmektedir. Buna bağlı olarak verim artışı, su tasarrufu ve risk yönetimi gibi alanlarda önemli kazanımlar sağlandığı görülmüştür. Türkiye'de ise dijital tarım uygulamalarının giderek yaygınlaşmasına rağmen, altyapı farklılıkları, çiftçilerin dijital okuryazarlık düzeyi ve yatırım maliyetleri gibi nedenlerle gelişmiş ülkelerle karşılaştırıldığında daha sınırlı bir yayılım olduğu anlaşılmaktadır. Son yıllarda yapılan kamu yatırımları, dijital destek programları ve özel sektör girişimleri bu alanda ilerlemeyi hızlandırsa da Türkiye'nin potansiyelini tam olarak kullanabilmesi için daha kapsayıcı ve sürekli destek mekanizmalarına ihtiyaç duyulduğu ortaya çıkmıştır. Araştırma sonuçlarına göre dijital tarım, çiftçilerin üretim kararlarını önemli ölçüde etkilemekte; daha bilinçli, veriye dayalı ve planlı bir üretim anlayışı gelişmesine katkı sağlamaktadır. Dijital araçları aktif kullanan çiftçilerin verimlilik, maliyet yönetimi ve sürdürülebilir üretim konusunda daha başarılı olduğu görülmüştür. Bu durum, dijitalleşmenin sadece bireysel üreticiyi değil, tarımsal politikaları da yeniden şekillendirdiğini göstermektedir. Politikaların veri temelli yapılara doğru ilerlemesi, destekleme modellerinde farklılaşmaya ve daha hedef odaklı stratejilere ihtiyaç duyulmasına yol açmaktadır. Genel olarak değerlendirildiğinde hem dünya genelinde hem de Türkiye'de dijital tarım, tarım sektörünün geleceğini belirleyen stratejik bir unsur hâline gelmiştir. Türkiye'nin bu dönüşümden maksimum faydayı sağlayabilmesi için altyapının güçlendirilmesi, çiftçilerin dijital becerilerinin artırılması ve tüm üreticilerin eşit şekilde bu teknolojilere erişebilmesini sağlayacak politikaların geliştirilmesi kritik öneme sahiptir. Dijital tarımın doğru şekilde yaygınlaştırılması hem çiftçilerin üretim davranışlarını iyileştirecek hem de ülkenin sürdürülebilir tarım hedeflerine ulaşmasını destekleyecektir. Dijital tarım teknolojileri, çiftçi davranışlarında köklü değişimlere neden olmakta ve tarımsal politikaların yeniden şekillendirilmesini zorunlu kılmaktadır. Teknolojiye dayalı karar alma, kaynak kullanımında verimlilik, risk yönetimi ve pazar entegrasyonu gibi açılardan çiftçilere önemli avantajlar sağlamaktadır. Bu çerçevede politika yapıcılar için öneriler şu şekildedir; çiftçilere yönelik sürekli eğitim ve yayım modelleri geliştirilmelidir. Dijital tarımda dijital okuryazarlık programları, çiftçilerin modern tarım teknolojilerini ve veri tabanlı uygulamaları etkin bir şekilde kullanabilmelerini amaçlar. Bu programlar, sensörler, IoT cihazları, yapay zeka uygulamaları ve tarımsal yazılımların nasıl çalıştığını öğretir. Ayrıca, veri analizi, dijital pazarlama ve çevrimiçi platformlar üzerinden bilgiye erişim konularında çiftçilerin becerilerini geliştirilmesine katkı sağlamaktadır. Dijital okuryazarlık, tarımda teknolojinin benimsenmesini hızlandırır, üretim verimliliğini artırır ve sürdürülebilir tarım uygulamalarının uygulanmasına katkı sağlar. Programlar aynı zamanda çiftçilerin karar alma süreçlerini destekleyerek riskleri azaltmakta ve kaynak kullanımını optimize etmektedir.

Altyapı Yatırımları: Kırsal bölgelerde geniş bant internet erişimi ve enerji altyapısı güçlendirilmelidir. Dijital tarımda altyapı yatırımları, teknolojik uygulamaların etkin bir şekilde kullanılabilmesi için gerekli fiziksel ve dijital temeli oluşturmayı hedefler. Bu yatırımlar; yüksek hızlı internet erişimi, sensör ve IoT cihazlarının kurulumu, veri depolama ve işleme sistemleri, akıllı sulama ve gübreleme sistemleri gibi modern tarım altyapılarını kapsamaktadır. Ayrıca, enerji kaynakları, bulut bilişim ve veri güvenliği çözümleri de

altyapının önemli bileşenlerindendir. Fiziki ve Sosyal Altyapı Yatırımları (KÖYDES, KIRDES), bilişim teknolojileri kullanımının yaygınlaştırılması, tarımsal verilerin gerçek zamanlı toplanmasını ve analiz edilmesini sağlar, karar alma süreçlerini hızlandırır ve üretim verimliliğini artırır. Altyapı yatırımları, dijital tarım teknolojilerinin sürdürülebilir bir şekilde uygulanmasına ve yaygınlaştırılmasına temel oluşturmaktadır (Özcan ve ark., 2020; T.C. Tarım ve Orman Bakanlığı, Tarım Reformu Genel Müdürlüğü, 2024).

Dijital Destekleme Mekanizmaları: Dijital ekipmanlara özel teşvikler, kredi ve hibe mekanizmaları oluşturulmalıdır. Dijital tarımda dijital destekleme mekanizmaları, çiftçilerin teknolojiyi benimsemesini teşvik eden ve verimliliği artırmayı amaçlayan finansal ve teknik araçları kapsamaktadır. Bu mekanizmalar arasında hibe programları, sübvansiyonlu krediler, devlet ve özel sektör destekli danışmanlık hizmetleri ile eğitim ve sertifikasyon programları yer alımaktadır. Tarım ve Orman Bakanlığı, akıllı tarım projelerine yönelik çeşitli hibe ve teşvik programları sunmaktadır. Özellikle Ar-Ge Destek Programı aracılığıyla, tarım sektöründe teknolojik yeniliklerin geliştirilmesi ve uygulanması teşvik edilmektedir. Bu program, özel sektörün Ar-Ge kültürünü ve kapasitesini artırmayı, yeni tür, çeşit, teknoloji ve ürünlerin geliştirilmesini amaçlamaktadır. Ayrıca, KOSGEB'in Ar-Ge ve İnovasyon Destek Programı, tarımsal teknolojiler geliştiren firmalara finansal destek sağlamaktadır. Örneğin, Görsentam firması bu program sayesinde, yapay zeka destekli tarım çözümleri geliştirerek ürün verimini artırmıştır. Ayrıca, tarımsal veri platformları ve yazılım çözümleri aracılığıyla üreticilere veriye dayalı karar alma imkânı sunulur. Bu destekler, dijital teknolojilerin sahada uygulanmasını kolaylaştırırken, üretim maliyetlerini düşürür ve sürdürülebilirliği artırmaktadır (Göl ve Tarhan 2023).

Ulusal Tarımsal Veri Platformu: Üretim verileri tek bir ulusal sistemde toplanmalı, analiz edilmeli ve politika yapıcıların kullanımına açılmalıdır. Dijital tarımda Ulusal Tarımsal Veri Platformu, tüm tarımsal üretim süreçlerinden toplanan verilerin merkezi bir sistemde birleştirilmesini sağlayan bir yapıdır. Bu platform, çiftçilere, KOBİ'lere ve politika yapıcılara veri temelli karar alma olanağı sunar; ürün izleme, toprak ve su yönetimi, iklim verileri, hastalık ve zararlı takibi gibi alanlarda rehberlik eder. Ayrıca, farklı veri kaynaklarının entegrasyonu sayesinde tarımsal üretimde verimliliğin artırılmasına ve kaynakların daha etkin kullanılmasına katkı sağlamaktadır (Pakdemirli ve ark., 2021).

Yerelleştirilmiş Dijital Çözümler: Bölgesel iklim ve toprak koşullarına uygun, çiftçi odaklı dijital uygulamalar geliştirilmelidir. Dijital tarımda yerelleştirilmiş dijital çözümler, bölgesel iklim, toprak yapısı, su kaynakları ve üretim koşullarına göre uyarlanmış teknolojik uygulamaları ifade etmektedir. Bu çözümler, çiftçilere kendi coğrafi ve ekolojik koşullarına uygun bilgi, araç ve öneriler sunarak verimliliği artırmayı hedeflemektedir. Örneğin, yerel bitki türleri için hassas sulama sistemleri, pest ve hastalık uyarı uygulamaları veya bölgesel gübreleme planları bu kapsama girmektedir. Ayrıca yerelleştirilmiş dijital çözümler, tarımsal üretimde riskleri azaltır, kaynak kullanımını optimize eder ve sürdürülebilirliği desteklemektedir (Çakmakçı ve Çakmakçı, 2021).

Yasal Çerçeve ve Veri Güvenliği: Tarımsal veri sahipliği, paylaşım standartları ve gizlilik hükümleri net şekilde düzenlenmelidir. Dijital tarımda yasal çerçeve, veri güvenliği ve mevzuatlar; verilerin toplanması, işlenmesi ve paylaşılmasında çiftçi verilerinin korunması, siber saldırılara karşı güvenliğin sağlanması ve izinsiz kullanımın önlenmesini kapsamaktadır. Bilgilerin güvenli bir şekilde yönetilmesi ve çiftçilerin dijital dönüşüm sürecinde karşılaşabileceği zorlukların minimize edilmesi için gereklidir (T.C. Tarım ve Orman Bakanlığı, 2025).

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DAIRY CATTLE IN THE CLIMATE CHANGE ERA: PRECISION LIVESTOCK FARMING AND DIGITAL SENSOR APPROACHES

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ABSTRACT

Global climate change is markedly increasing the severity of thermal stress in dairy cattle due to rising ambient temperatures and relative humidity levels. Thermal stress arises when the balance between metabolic heat production and environmental heat load is disrupted, resulting in a wide range of physiological consequences such as decreased feed intake, reductions in milk yield and composition, impaired reproductive performance, and elevated stress levels. This situation not only exacerbates production losses but also negatively affects animal welfare, creating multidimensional challenges for the sustainability of dairy farming. In recent years, the development of precision livestock farming technologies has made it possible to monitor environmental, physiological, and behavioral parameters of cattle in real time through environmental sensor systems, wearable biometric monitoring devices, and thermal imaging techniques. These technologies allow high-resolution, continuous monitoring of indicators such as body surface temperature, respiration rate, activity patterns, rumen function, heart rate, feeding behavior, and environmental heat load. When this sensor-based data flow is integrated with machine learning algorithms and decision support systems, it enables the early detection of heat stress, the objective classification of welfare status, and the development of adaptive management strategies that minimize production losses. This study addresses the thermal stress pressure imposed by climate change on dairy cattle, explains the scientific basis of the associated physiological responses, and provides a comprehensive evaluation of the application capacity and sustainability relevance of advanced sensor-based technologies used to monitor environmental, physiological, and behavioral parameters.

Keywords: Climate change; dairy cattle; thermal stress; digital sensor technologies; precision livestock farming; environmental monitoring.

I. INTRODUCTION

Although the Earth's climate has undergone natural fluctuations throughout human history, the warming trend observed in recent decades has begun to exert pronounced impacts on agricultural and livestock production systems. Global mean temperatures have risen by approximately 0.5-0.8°C since the 1860s, and projections indicate that this increase may reach 2°C by the end of the century if current trajectories persist (Kadıoğlu and Dokumacı, 2005; Özen, 2008). Within the context of dairy cattle production, increasing ambient temperatures and greater environmental variability substantially intensify heat stress, which in turn leads to reductions in milk yield, alterations in milk composition, impaired reproductive performance, and broader welfare challenges. Consequently, precision livestock farming (PLF) strategies and digital sensor-based monitoring technologies have become essential tools for safeguarding animal well-being and mitigating productivity losses. These technologies enable continuous assessment of physiological and environmental indicators, thereby supporting more resilient, adaptive, and sustainable management practices in modern dairy farming.

Between 1970 and 2023, the global cattle population increased from 1.08 billion to 1.58 billion head, representing an overall rise of approximately 46%; however, a clear deceleration in this upward trend has been evident particularly after 2010 (FAO, 2024). The trajectory observed in Türkiye closely mirrors this global pattern. According to TUIK (2024), the national cattle population-characterized by steady growth during the 1961-1980 period-declined to 10.76 million head in the 1990-2000 interval. Yet, following the implementation of targeted support schemes, genetic improvement initiatives, and modernization efforts across livestock production systems, cattle numbers began to recover after 2010, ultimately reaching a historical peak of 17.96 million head in 2020. Despite this temporary recovery, the decline to 16.42 million head after 2020 reflects the growing pressure exerted on livestock production by the intensifying impacts of climate change, consistent with global developments. Increasing temperatures, prolonged drought events, and fluctuations in feed crop production have emerged as major constraints limiting sustainable growth in livestock systems both worldwide and in Türkiye. Trends in global milk production exhibit a comparable pattern. Worldwide milk output rose from 391.9 million tons in 1970 to 968.2 million tons in 2023, marking roughly a 2.5-fold increase. Particularly after 2010, the widespread adoption of data-driven herd management tools, sensor-based monitoring technologies, automated milking systems, and digital surveillance platforms played a decisive role in accelerating production growth; consequently, between 2010 and 2023, global milk production expanded by 33% (FAO, 2024). Türkiye shows a similar tendency: national milk production increased from 7.3 million tons in 1970 to 21.4 million tons in 2023, nearly a threefold rise (TUIK, 2024).

Rojas Downing et al. (2017) emphasize that global demand for products of animal origin is projected to intensify in the coming decades. If current consumption trends continue, producers will need to increase output by approximately seventy percent over the next fifty years. Meeting this rising demand requires a stronger livestock production capacity and an agricultural infrastructure capable of supporting sustainable food supply systems. Long term sustainability in livestock production depends on the adoption of management practices that support resilience to heat stress, the preservation of high performing genetic resources, and the integration of automation and digital technologies into routine farm operations. Smart farming innovations highlighted by Alipio and Villena (2023) contribute significantly to this transformation, offering high accuracy and operational efficiency in the monitoring of animal health. Wearable smart devices and biosensors that rely on minimally invasive designs allow early identification of diseases and continuous monitoring of physiological and behavioral indicators. These technologies enhance the responsiveness of farm management and provide

objective real time assessments of herd well-being. Their expanding use reflects a broader shift toward data oriented and technology supported livestock production systems.

This study investigates the mechanisms of thermal stress observed in dairy cattle under the increasingly severe impacts of climate change within an integrated framework, and evaluates the innovative opportunities offered by advanced sensor technologies and digital monitoring systems for the early detection and effective management of this stress.

II. MECHANISMS OF THERMAL STRESS IN DAIRY CATTLE

Thermal stress arises when the metabolic heat produced by dairy cattle exceeds their capacity to dissipate heat to the surrounding environment, leading to an elevation in body temperature beyond the normal physiological range. Bernabucci et al. (2010) describe this condition as the cumulative external heat load acting on the animal and emphasize that thermal stress functions as a major environmental factor that challenges the ability of the organism to maintain homeothermic balance. The Temperature Humidity Index, commonly referred to as THI, represents one of the most widely used indicators for assessing thermal load. Hahn et al. (2009) highlight the essential role of THI in distinguishing among normal, moderate, severe and emergency levels of stress. Such classifications provide a foundational framework for identifying early responses to heat in field conditions and for guiding the development of appropriate management strategies. Thermal stress influences a wide range of physiological functions in dairy cattle, including feed intake, body temperature regulation, milk production, reproductive performance and behavioral responses (Cook et al., 2007; Tucker et al., 2008; Rhoads et al., 2009). Cows exposed to heat stress typically show reductions in feed intake and rumination activity (Grant and Miner, 2015), along with disruptions in energy metabolism, impaired lactation physiology and declines in fertility (Thatcher et al., 2010; Roth, 2020). Garner et al. (2017) report that thermal load exerts an even stronger suppressive effect on lactation during estrus periods. These findings indicate that heat stress contributes not only to short term productivity losses but also to longer term challenges related to reproductive efficiency.

At the physiological level, disruption of thermal balance triggers increases in respiration rate, elevations in body temperature, acceleration in heart rate and greater evaporative heat loss through sweating (Aloia et al., 2024). Becker et al. (2020) report that heat stress in Holstein cows reduces concentrate intake by five percent, forage intake by twenty two percent and the energy available for milk synthesis by thirty to fifty percent. These outcomes indicate that greater thermal load substantially limits overall productive capacity through decreased feed intake and reduced efficiency of energy utilization. Thermal stress also produces marked alterations in both the quantity and composition of milk. Chen et al. (2024) show that reduced dry matter intake under heat stress directly diminishes milk yield and negatively affects milk composition. Kadzere et al. (2002) identify an optimal temperature range of five to twenty five degrees Celsius for lactating cows, and Michael et al. (2022) note that temperatures exceeding this range, especially under high humidity, can cause reductions in milk yield of ten to forty percent. These findings demonstrate the close interaction among environmental temperature, energy metabolism and rumen function, and reveal that even modest changes in the thermal environment can generate significant consequences for milk production.

Behavioral responses under thermal stress closely parallel the physiological indicators observed in dairy cattle. Polsky and von Keyserlingk (2017) report that cows exposed to heat stress show reduced feed intake, increased water consumption, altered patterns of lying and standing and greater use of shaded areas. These behavioral adjustments reflect attempts by the animal to reduce excessive heat load. Silanikove (2000) emphasizes that effective management

of heat stress begins with integrated monitoring of both behavioral and physiological responses. Identification of thermal thresholds that are critical for animal welfare enhances understanding of cattle sensitivity to heat stress. Yan et al. (2021) demonstrate that changes in body temperature and respiration rate provide important signals under varying environmental conditions, while Heinicke et al. (2019) show that individual activity responses serve as valuable indicators for early detection of accumulated thermal load. Armstrong (1994) offers a functional framework for interpreting the Temperature Humidity Index by classifying values below 71 as the comfort zone, values from 72 to 79 as mild stress, values from 80 to 90 as moderate stress and values above 90 as severe stress. Zimbelman et al. (2009) reveal that reductions in milk yield can begin even when the Temperature Humidity Index reaches 65, indicating that high producing dairy cows may experience performance losses at considerably lower thresholds. Taken together, these findings show that the Temperature Humidity Index functions not only as an indicator of environmental conditions but also as a critical decision parameter for the early identification of production losses and for the continuous assessment of animal welfare.

When these findings are considered collectively, it becomes evident that thermal stress disrupts physiological, metabolic and behavioral processes in dairy cattle at the same time, leading to substantial impairments in both welfare and productive performance. As a result, the integration of precision livestock technologies is regarded as a strategic necessity in modern dairy production rather than a mere innovation, since timely, highly sensitive and objective monitoring of these multilayered stress responses is essential for effective management.

III. DIGITAL TRANSFORMATION IN DAIRY CATTLE PRODUCTION AND APPLICATIONS OF PRECISION LIVESTOCK FARMING

Rising environmental temperatures associated with global warming place substantial pressure on the ability of farm animals to maintain homeothermal balance, and this challenge increasingly amplifies the negative effects of heat stress on physiological, behavioral and metabolic functions. The decline in productive performance, disruption of metabolic stability and reduction in welfare caused by heat stress have positioned this phenomenon as a major limiting factor in modern dairy farming. Early identification and effective management of thermal stress hold critical importance, both for reducing biological losses and for supporting the economic sustainability of dairy operations. Continued increases in temperature driven by climate change compel dairy farms to adopt more innovative and data-oriented management strategies. In this context, digitalization offers comprehensive solutions for mitigating the impacts of heat stress through real time monitoring and predictive analytics. These approaches enable more accurate detection of stress conditions and support proactive decision making aimed at safeguarding herd health and productivity (Neculai Valeanu et al., 2024).

In modern dairy herds, the need for precise data collection is becoming increasingly important for improving productivity and enhancing the accuracy of management decisions. Liu et al. (2023) emphasize that sensor-based monitoring technologies have gained critical relevance, as animal behavior is closely linked to overall health status. Advances in the Internet of Things, artificial intelligence and computer vision have enabled integrated analysis of data obtained from image, sound and motion sensors, resulting in substantial improvements in both the accuracy and continuity of herd management. Among the physiological responses associated with thermal stress, respiration rate stands out due to its sensitivity to environmental variation and its rapid adjustment capacity, making it a reliable indicator for early detection. Hoffmann et al. (2020) report that modern sensor technologies can monitor essential parameters such as respiration rate, body temperature, heart rate and activity level with high accuracy, thereby

supporting the development of data driven early warning systems. Findings from a climate-controlled experiment conducted by Zhou et al. (2022) show that once ambient temperature rises above 28 degrees Celsius, evaporative heat loss accounts for 70 to 80 percent of total heat dissipation and heat exchange associated with respiration increases by 34 percent within the temperature range of 16 to 32 degrees Celsius. These results strongly confirm the role of respiration rate as a key physiological marker for the early identification of thermal stress.

The multidimensional nature of heat stress involves not only fluctuations in environmental conditions but also dynamic variations in individual physiological and behavioral responses. This complexity demonstrates the limitations of traditional herd management approaches under modern production conditions and highlights the growing importance of Precision Livestock Farming. Precision Livestock Farming represents an integrated system based on information and communication technologies that enable real time collection, analysis and interpretation of extensive data related to animal and environment interactions (Banhazi et al., 2012; Tekin et al., 2021). The opportunities created by digitalization have become a strategic necessity for contemporary dairy operations, particularly in response to increasing expectations for sustainability, productivity and improved animal welfare (Liu et al., 2023; Jiang et al., 2023).

Wearable sensor technologies constitute a central component of Precision Livestock Farming and enable continuous and detailed monitoring of behaviors such as rumination, grazing, feeding and activity levels. Reiter et al. (2018) and Gehlot et al. (2022) report that accelerometer-based sensors provide high accuracy in predicting various diseases by identifying early shifts in behavioral patterns. Dzermeikaite et al. (2023) also indicate that sensor-based systems contribute significantly to reducing stress, improving welfare and preventing related economic losses. In cattle, ear tags, pedometers, rumen boluses and collar mounted sensors offer practical advantages due to their relatively large surface areas for attachment and represent economical tools capable of delivering continuous data at the individual animal level (Halachmi et al., 2019; Lamanna et al., 2025).

Multisensor systems based on the Internet of Things that enable simultaneous evaluation of environmental and behavioral indicators represent an essential component of Precision Livestock Farming. Pons et al. (2017) and Leliveld et al. (2024) demonstrate that variables related to barn microclimate, including temperature, humidity, carbon dioxide concentration, wind speed, water consumption and bedding characteristics, can be monitored at high resolution along with behaviors such as lying, standing, feeding and rumination. This integrated approach markedly enhances early warning capacity and supports rapid detection of stress related changes. By providing timely and effective intervention opportunities against environmental stressors, the approach has become a core element of the digital transformation occurring in modern dairy farming. Noninvasive sensor technologies developed for continuous and accurate monitoring of health status in dairy cattle allow measurement of physiological and behavioral parameters without any physical intervention to the animal and form the foundation of contemporary monitoring systems, as illustrated in Figure 1. The integration of Internet of Things architectures with cloud computing, edge computing and machine learning algorithms enables continuous assessment of data streams and supports the automation of decision-making processes in herd management (Tangorra et al., 2024; Aloia et al., 2024).

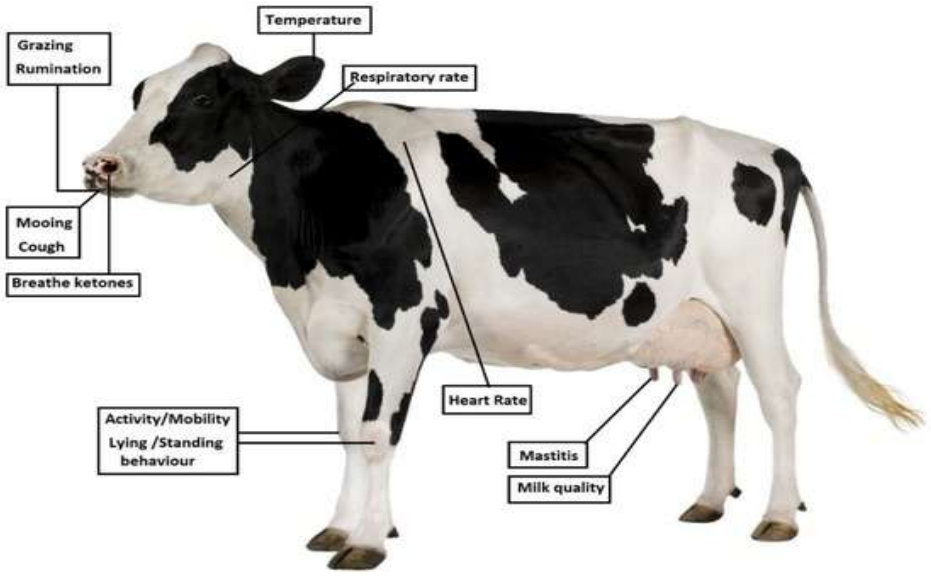

Figure 1. Core Components of Noninvasive Sensor Technologies Used for Monitoring Health in Dairy Cattle (Awasthi et al., 2016).

Machine learning provides substantial advantages for the analysis of multidimensional data sets obtained from sensors. Jensen et al. (2016) combined a dynamic linear model with a Naive Bayes classifier for early detection of mastitis and achieved a sensitivity of 80 percent and a specificity of 81 percent, representing a clear improvement compared with conventional monitoring methods. Pacheco et al. (2020) show that neural network models offer much higher accuracy, reaching 83 to 84 percent, for predicting heat stress compared with traditional indices such as the Temperature Humidity Index. In behavior-based estrus detection, a fuzzy logic model developed by Memmedova and Keskin (2011) achieved an accuracy of 98 percent, demonstrating the strong potential of this approach. Michie et al. (2020) note that direct measurement of feed intake is not always practical, yet accelerometer-based collars can estimate feeding time and provide a reliable indirect indicator of welfare related changes.

When all of these findings are considered together, digital transformation fundamentally reshapes the management paradigm of dairy farming systems. Sensor technologies based on the Internet of Things, together with artificial intelligence and machine learning applications, enable decisions related to animal welfare, health status and productive performance to be made more rapidly, more accurately and with greater predictability. Early identification of heat stress, automatic detection of changes in behavioral patterns and the implementation of data driven management models significantly reduce both biological losses and economic risks. The increasing adoption of Precision Livestock Farming practices is becoming a cornerstone of future dairy operations that aim to be sustainable, efficient and oriented toward high levels of animal welfare.

IV. RESEARCH FINDINGS AND DISCUSSION

This study demonstrates that climate change accelerates the onset of thermal stress in dairy cattle and that this condition produces multifaceted negative effects on animal health, welfare and productive performance. In the literature, Bernabucci et al. (2010) and Hahn et al. (2009) report that thermal load disrupts metabolic balance and restricts the physiological capacity of cattle, while Zimbelman et al. (2009) indicate that modern high yielding herds may experience productivity losses even at a Temperature Humidity Index of 65. These findings show that

climatic sensitivity is higher than previously assumed and that traditional management practices are insufficient under these emerging environmental conditions.

The effects of heat stress on feed intake, milk yield and reproductive performance have been confirmed by numerous studies. The reductions in feed intake ranging from 5 to 22 percent reported by Becker et al. (2020) and the productivity losses demonstrated by Chen et al. (2024) reveal that thermal load has critical economic implications for dairy production systems. Behavioral changes, including increased water consumption, greater use of shaded areas and irregularities in lying and standing times, have been documented by Polsky and von Keyserlingk (2017), who emphasize the importance of these responses as indicators for welfare assessment. Within this context, digital sensor technologies and Precision Livestock Farming applications play a strategic role in the management of thermal stress. Multisensor systems based on the Internet of Things enhance early warning capacity by monitoring environmental variables such as temperature, humidity, carbon dioxide concentration and bedding conditions together with behavioral indicators (Pons et al., 2017; Leliveld et al., 2024). Machine learning models have also shown superior accuracy compared with classical methods, particularly in the early prediction of heat stress and disease conditions (Jensen et al., 2016; Pacheco et al., 2020).

V. CONCLUSION

In conclusion, sustainable dairy farming increasingly requires data driven monitoring, rapid diagnosis and adaptive management strategies. Although digital sensor systems alone cannot fully address the challenges posed by thermal stress, their integration with appropriate housing design, ventilation, cooling and feeding management yields highly effective outcomes. Future research should focus on hybrid monitoring systems that combine multiple sensor data streams and on sensitivity analyses for different breeds and production models under changing climatic conditions.

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THE ROLE OF STORAGE INFRASTRUCTURE IN STRATEGIC AGRICULTURAL COMMODITIES: THE STRUCTURE OF GRAIN PRODUCTION AND LICENSED WAREHOUSING IN TÜRKİYE

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ABSTRACT

Grain is a central strategic commodity within Türkiye's agricultural production system, serving as a key input for food security, livestock nutrition and agro industrial processing. However, climate related yield fluctuations, increasing input costs, regional variability in grain based cropping patterns and structural inefficiencies throughout the agricultural marketing chain create volatility in grain markets and weaken producer income stability. United Nations projections estimating a global population of 8.1 billion by 2025 further highlight the urgency of strengthening food supply security at national and global levels. Despite this need, major inefficiencies persist across the global agri food supply chain. In 2022, approximately 1.05 billion tons of food, equal to 19 percent of global production, was lost or wasted, while 783 million individuals faced undernutrition. This imbalance exposes significant vulnerabilities in post-harvest and distribution stages. Nearly 13 percent of losses occur during the post-harvest period, especially in cereals where inadequate storage engineering, improper handling, suboptimal transport conditions and insufficient moisture and aeration control accelerate deterioration caused by microbial activity and storage pests. Within this context, the licensed warehousing system acts as an essential post-harvest management mechanism by providing controlled storage environments, reducing losses, lowering supply pressure during harvest peaks, supporting quality standardization and improving agricultural supply chain governance. Türkiye currently hosts 475 warehouse enterprises, including 260 licensed facilities. Licensed storage capacity has reached 13.95 million tons, while total planned capacity stands at 26.48 million tons. Cereals, legumes and oilseeds record the highest utilization levels, with Konya leading at 16 percent, followed by Diyarbakır and Mardin. Between 2018 and 2024, Electronic Product Certificate (ELÜS) transactions increased twenty fourfold, indicating rapid system expansion. Licensed warehousing therefore functions not only as storage infrastructure but also as a strategic institutional component that strengthens agricultural economic resilience and reduces external dependency.

Keywords: Grain, storage, licensed warehousing, food security, Electronic Product Certificate (ELUS), global and regional market comparison

I. INTRODUCTION

Cereals have played a critical role since the dawn of civilization, serving as a fundamental food component both for direct human consumption and as an essential input in animal feed used for livestock production. Şanlıer (2013) states that approximately 55-65% of the daily global energy requirement and about 66% of the daily protein intake are met by cereal-based products, underscoring the fact that cereals constitute an indispensable strategic product group for global food security. Beyond being the primary source of energy and nutrients for human diets, cereals also provide crucial inputs for various economic sectors, including livestock production, food processing industries, and biofuel manufacturing. Therefore, the sustainability of cereal production, its support through efficient storage systems, and the delivery of cereals to consumers within stable market structures are fundamental components of national food supply security policies.

In recent years, climate change has increasingly influenced all stages of the agricultural production chain, exerting significant pressure on the continuity of cereal production. Rising temperatures, shifts in precipitation patterns, and the increasing frequency of extreme weather events have led to yield losses, declines in product quality, and fluctuations in overall output. Climate projections for Türkiye indicate that these changes will cause notable decreases particularly in barley, wheat, and maize production. Indeed, modeling studies suggest that yield increases in wheat will nearly stagnate by the 2030s, while maize production is expected to decline by approximately 10% by 2050 (Voyvoda et al., 2017). All these findings demonstrate that climate change–induced production fluctuations necessitate a re-evaluation not only of the agricultural production process itself but also of storage infrastructure planning, capacity expansion, and stock management strategies. In this context, addressing the impacts of climate change on cereal production and storage systems through a holistic approach is of critical importance for both national food security and agricultural sustainability.

According to United Nations projections, the world population is expected to reach approximately 8.1 billion people by 2025. This demographic increase further underscores the growing importance of global food security (UN, 2025). However, the fact that 1.05 billion tons of food were wasted worldwide in 2022, which corresponds to about 19 percent of the total amount of food produced, demonstrates the fragility of global food systems (UNEP, 2024). When this situation is considered together with the continued struggle of 783 million people facing inadequate nutrition in the same year, it becomes increasingly clear that food losses and food waste represent a critical challenge to global sustainability (FAO, 2023).

The rapid increase in population both worldwide and in Türkiye, the changes in per capita consumption patterns, and the contraction of agricultural production areas due to environmental, socioeconomic and political factors lead to periodic fluctuations in cereal supply. These fluctuations do not arise solely from the production stage. The high levels of losses occurring in the period after harvest also place considerable pressure on supply. FAO (2023) reports that global post-harvest cereal losses range between 10 and 15 percent, and that these rates can rise to as high as 20 percent in developing countries. Similarly, Philips and Throne (2010) state that losses occurring during storage reach approximately 10 to 20 percent of total production and that these losses mainly result from insufficient preparation before harvest, inadequate storage infrastructure and damage caused by insects and other pests. The study conducted by Bala (2016) also shows that annual cereal loss throughout the chain from harvest to consumption ranges from 10 to 25 percent and emphasizes that reducing these losses depends on proper threshing, cleaning, drying and storage under suitable conditions. When these findings are evaluated together, it becomes evident that cereal supply security is

associated not only with production volume but also with effective post-harvest management and storage practices that minimize loss rates. These findings demonstrate that reducing losses throughout the production and storage chain is of great importance for ensuring the sustainable security of food supply.

Due to these characteristics, cereals are regarded as a strategic group of agricultural products, and not only the volume of production but also the ability to store the harvested crop in a safe and high-quality manner is considered a decisive factor for national food supply security. In this context, licensed warehouses make a significant contribution by enabling products to be preserved under conditions that comply with established standards, thereby reducing losses caused by spoilage, decay and damage from harmful organisms.

Among the primary reasons for the development of the licensed warehousing system in Türkiye are the provision of reliable storage facilities for producers, the prevention of sudden and unbalanced entry of surplus supply into the market during harvest periods, the preservation of product quality in accordance with standards and the support of price stability in the market. In addition, the facilitation of access to finance through product certificates stands out as a factor that further strengthens the economic and structural necessity of the system (TEBGE, 2024). In this regard, enhancing the functionality and capacity of the licensed warehousing system emerges as one of the key areas of improvement within national food security policies in order to ensure the sustainability of cereal production and the supply chain in the face of climate change, population growth and structural market conditions.

II. CEREAL PRODUCTION TRENDS IN THE WORLD AND IN TÜRKIYE

Global cereal production has generally shown an upward trend in recent years. However, significant differences emerge between years due to variability in climatic conditions, production costs, contractions in cultivated areas and fluctuations in the supply and demand structure. According to WASDE data, global cereal production increased by 5.9 percent over the past decade, rising from 2190 million tons to 2320 million tons (Table 1). This increase is considered to be the result of technological developments in agricultural productivity and the expansion of production capacity. Within the cereal group, maize and wheat constitute the largest share of global production. Approximately 87.5 percent of total cereal production worldwide consists of these two products, with maize accounting for about 53 percent and wheat for about 34 percent. This situation reflects the high level of demand for these products both in human nutrition and in the feed and industrial sectors. Barley, although having a more limited production volume, continues to be an important component of livestock production and the beer and malt industry with its 6 percent share.

Table 1. Change in World Cereal Production by Years (Million Tons) (WASDE, 2025)

Product/ Years	2016/17	2017/18	2018/19	2019/20	2020/21	2021/22	2022/23	2023/24	2024/25
Wheat	757	761	732	760	773	780	803	794	799
Maize	1136	1094	1133	1133	1139	1224	1167	1233	1233
Barley	148	143	140	159	160	146	153	144	143
Rice	493	495	499	499	509	515	517	524	540
Other	149	143	139	143	159	146	147	140	145
Total (Rice except)	2190	2141	2144	2195	2231	2296	2270	2311	2320

Cereal production in Türkiye has demonstrated a sustained upward trajectory, registering an 11% increase between 2016 and 2025, from 34.3 million tons to 38.2 million tons (IGC, 2025). A disaggregated assessment of crop composition indicates that maize and wheat jointly constitute approximately 75.9% of the national cereal output. Within this structure, maize represents the predominant component with a share of roughly 54.4%, whereas wheat accounts for 21.5% (Table 2). This compositional profile evidences the centrality of maize and wheat in Türkiye's cereal production system and reinforces their strategic significance for sectoral resource allocation, yield optimization strategies, and long-term agricultural planning.

Table 2. Annual Variation in Cereal Production in Türkiye (Million Tons) (IGC, 2025)

Product/ Years	2016/17	2017/18	2018/19	2019/20	2020/21	2021/22	2022/23	2023/24	2024/25
Wheat	20,6	21,5	20	19	19,5	17,6	19,7	22	20,8
Maize	6,4	5,9	5,7	6	6,5	6,7	8,5	9	8,2
Barley	6,7	7,1	7	7,6	8,3	5,7	8,5	9,2	8,2
Rice	0,50	0,52	0,61	0,61	0,59	0,54	0,60	0,54	0,58
Other	0,6	0,7	0,7	0,7	0,8	0,8	1	1,1	1
Total (Rice except)	34,3	35,2	33,4	33,3	35,1	30,8	37,7	41,3	38,2

In Türkiye, the production trajectories of major cereal commodities have exhibited periodic fluctuations over the past decade, reflecting the interaction between agro-ecological variability and production system characteristics. Wheat output demonstrates interannual instability, with yield gains in climatically favorable seasons and measurable contractions during years affected by temperature and precipitation anomalies. Barley production shows even higher climate sensitivity, experiencing pronounced declines during drought episodes, thereby underscoring the crop's dependence on intra-seasonal rainfall distribution and its limited resilience under water-deficit conditions (TUIK, 2024). Conversely, maize production has followed a consistent upward trend, largely driven by its concentration in regions equipped with modern, pressurized irrigation technologies. Enhancements in irrigation infrastructure and water management efficiency have contributed significantly to yield stabilization and productivity gains, aligning maize production with intensive, input-responsive agricultural systems.

From a demographic perspective, the global population is estimated to have reached 8.23 billion in 2025, while Türkiye, with a population of 87.7 million, accounts for approximately one percent of the world's population (UN, 2025; TUIK, 2024). In the same year, Türkiye's cereal production corresponds to roughly 1.6% of global cereal output. Worldwide per capita cereal production stands at 281.7 kilograms annually, whereas this figure reaches 435.5 kilograms in Türkiye. The fact that Türkiye's per capita production level is approximately 55% higher than the global average indicates that the country contributes to global cereal production at a proportionally greater rate than its share of the world population. This situation underscores Türkiye's strong agricultural production potential at both regional and global scales.

III. STRUCTURAL ANALYSIS OF THE CEREAL MARKET IN TÜRKİYE

According to TEBGE (2024) data, an examination of barley statistics for the 2018-2023 period reveals notable shifts influencing both the production structure and the external trade balance

of the sector. Although barley yield increased by only 5% over this five-year interval, the harvested area and total output expanded by 22%, indicating that production growth was primarily driven by area expansion rather than productivity gains. During the same period, consumption rose by 28%, reflecting a substantial increase in feed demand and demonstrating that barley has become an increasingly critical input for the livestock sector (Table 3).

Table 3. Fundamental Indicators of Barley Production in Türkiye (TEBGE, 2024)

Years	Area	Yield	Production	Consumption	Feed Use	Stock Change	Imports	Exports	Self-Sufficiency
2018/19	26.119	268	7.000	6.951	85,7	-145	522	295	94,7
2019/20	28.691	265	7.600	7.536	86,0	552	978	35	94,8
2020/21	30.972	268	8.300	8.035	86,0	458	790	99	97,1
2021/22	31.691	181	5.750	8.095	85,8	94	2.989	205	66,8
2022/23	31.995	281	8.500	8.873	86,3	1.120	2.264	261	90,0

*Area, production: thousand da, Yield: kg/da, consumption, stock change, imports, exports: thousand tons, Self-Sufficiency: %

Barley production in Türkiye exhibits a regionally concentrated structure, with the Central Anatolia Region holding a strategically dominant position due to its substantial contribution to national output. Data from 2023 indicate that Konya ranks first with a production share of 15.1%, followed by Ankara with 8.5%. Kayseri and Şanlıurfa each account for 4.2% of total production, demonstrating that barley cultivation is geographically clustered and shows a pronounced regional concentration pattern (Figure 1). Developments in barley prices further complement this geographically concentrated production structure, revealing a distinct upward trajectory over time. The persistent increase in barley prices across years highlights the continuous escalation of agricultural commodity prices at both the farm and market-institutional levels. Examination of Figure 1 shows that all three-price series remained at relatively low and closely aligned levels during the 2021/22 marketing year, whereas in 2022/23 prices nearly doubled compared to the previous year. This upward trend continued into the 2023/24 period, indicating a transition toward a sustained high-price regime in the barley market, driven by cost structures and shifts in supply-demand dynamics.

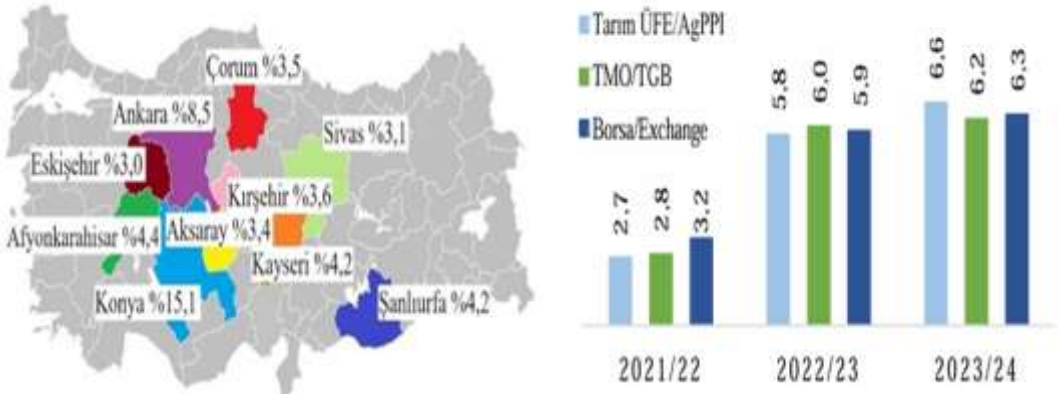


Figure 1. Distribution of Provincial Contributions to Barley Production and Trends in Barley Prices (TL/kg) (TEBGE, 2024)

Wheat is a strategic agricultural commodity in Türkiye and worldwide due to its status as a fundamental food source, its central role as a primary input for several agro industrial sectors such as flour and bakery production, and its function as a complementary feed ingredient in

livestock systems. Within this context, the fact that Türkiye produced approximately 22 million tons of wheat in the period from 2023 to 2024 is of critical importance for national food supply security (IGC, 2025). An examination of the geographical distribution of production shows that Konya accounts for 10.2 percent of national output, followed by Şanlıurfa with 7.8 percent and Ankara with 5 percent. This distribution demonstrates that wheat cultivation in Türkiye is concentrated in specific provinces (Figure 2). Although the self-sufficiency ratio reached 96 percent in the years 2022 and 2023, which may be viewed as a positive development, the decline in per capita wheat consumption to 178.6 kilograms indicates changes in demographic dynamics and dietary preferences. During the same period, imports increased by 89 percent, yields increased by 9 percent, consumption increased by 3 percent and exports increased by 2 percent. These changes suggest that both domestic and external demand for wheat have strengthened, thereby increasing the economic significance of the crop. However, the 1 percent decline in production and the 9 percent contraction in sown area point to a structural reduction that may create risks for long term supply security when the strategic nature of wheat is taken into account (Table 4). In addition, wheat prices have continued to rise across years. The simultaneous increase in the Agricultural Producer Price Index, the Turkish Grain Board procurement prices and the prices recorded in commodity exchanges indicates growing cost pressures throughout the agricultural sector. As shown in Figure 2, prices offered by the Turkish Grain Board were at the lowest level, while exchange prices were at the highest level in the period from 2021 to 2022. In the period from 2022 to 2023, all price indicators recorded an increase ranging from approximately two times to three times the level of the previous year. The continuation of high values for all indicators in the period from 2023 to 2024 indicates the establishment of a persistent high price structure in the wheat market, driven by production costs, supply and demand conditions and broader market forces.

Table 4. Fundamental Indicators of Wheat Production in Türkiye (TEBGE, 2024)

Years	Area	Yield	Production	Consumption	Feed Use	Stock Change	Imports	Exports	Self-Sufficiency
2018/19	72.993	274	20.000	18.805	2.212	-1.311	6.468	7.873	100,5
2019/20	68.463	278	19.000	20.070	2.267	1.148	10.793	7.531	89,5
2020/21	69.222	296	20.500	18.934	2.339	1.093	8.238	7.584	102,3
2021/22	67.447	262	17.650	19.115	2.145	-808,6	9.525	7.898	87,3
2022/23	66.287	298	19.750	19.373	2.453	3.380	12.208	8.028	96,0

*Area, production: thousand da, Yield: kg/da, consumption, stock change, imports, exports: thousand tons, Self-Sufficiency: %

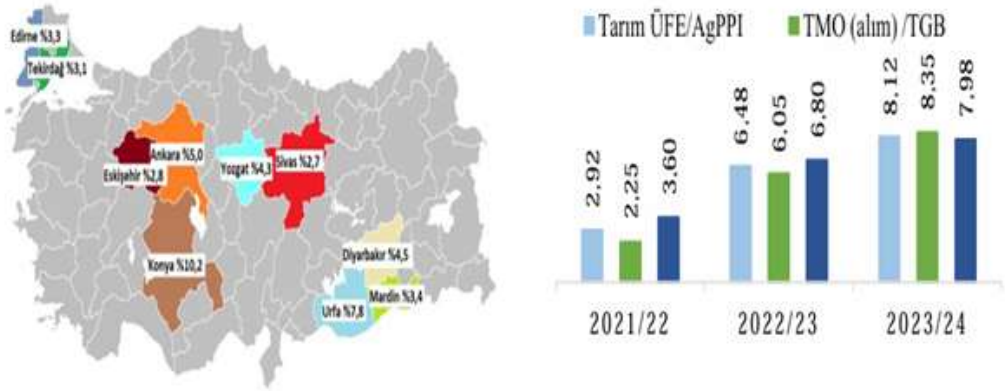


Figure 2. Distribution of Provincial Contributions to Wheat Production and Wheat Price Levels (TL per kg) (TEBGE, 2024)

Türkiye's maize production reached a record level of 9 million tons in the 2023 to 2024 period, underscoring the strategic importance of the country's expanding agricultural production capacity for national food supply security. The 54 percent increase in sown area and the 49 percent rise in total output strengthened Türkiye's maize production potential, while the improvement in the self-sufficiency ratio to 85.8 percent in 2022 to 2023 indicates that a larger share of domestic demand has been met through national production. In contrast, the 27 percent decline in imports and the 16 percent reduction in consumption suggest that market balances shifted in favor of domestic supply. At the same time, the 3 percent decrease in yield highlights the continuing influence of climatic and structural factors on production performance (Table 5). The concentration of production in Konya with 22.7 percent, Şanlıurfa with 11.8 percent and Adana with 11.1 percent demonstrates the critical role of specific agricultural basins in shaping Türkiye's national maize supply and emphasizes the strategic importance of regional production capacity. Moreover, when production and pricing indicators are evaluated together, it becomes evident that both regional production concentration and increasing cost pressures have contributed to the formation of a persistent high price structure in the maize market (Figure 3).

Table 5. Fundamental Indicators of Maize Production in Türkiye (TEBGE, 2024)

Years	Area	Yield	Production	Consumption	Feed Use	Stock Change	Imports	Exports	Self-Sufficiency
2018/19	5.919	963	5.700	7.866	6.451	-151	3.682	1.496	70,3
2019/20	6.388	939	6.000	7.706	6.376	114	2.720	720	75,5
2020/21	6.916	940	6.500	7.430	5.990	-327	1.814	1.017	84,9
2021/22	7.582	890	6.750	8.552	7.100	286	3.561	1.270	76,6
2022/23	9.119	932	8.500	6.611	8.019	-259	2.697	1.591	85,8

*Area, production: thousand da, Yield: kg/da, consumption, stock change, imports, exports: thousand tons, Self-Sufficiency: %

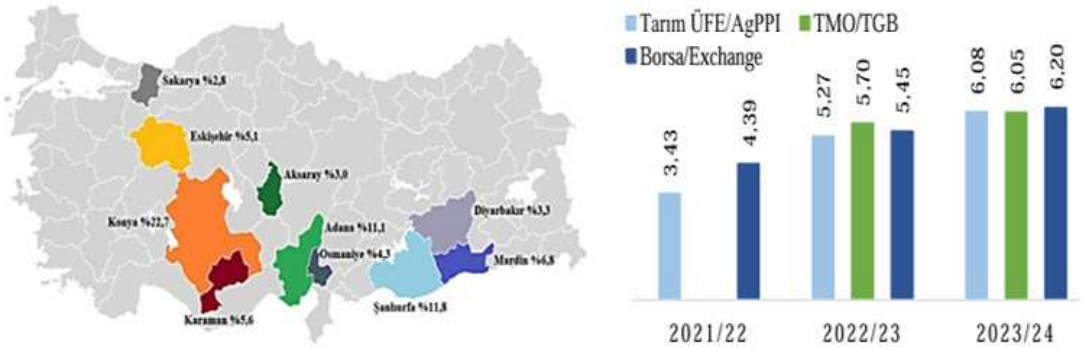


Figure 3. Distribution of Provincial Contributions to Maize Production and Maize Price Levels (TL per kg) (TEBGE, 2024)

In conclusion, the increase in production of these strategically important crops enhances the effective functioning of the licensed warehousing system. The ability to store the growing production volume in accordance with quality standards, to mitigate market volatility and to facilitate producers' access to finance through electronic warehouse receipts (ELUS) further strengthens the critical role of licensed warehouses. Therefore, both production growth and national supply security objectives make the reinforcement of the licensed warehousing

infrastructure indispensable for agricultural market stability and sustainable resource management.

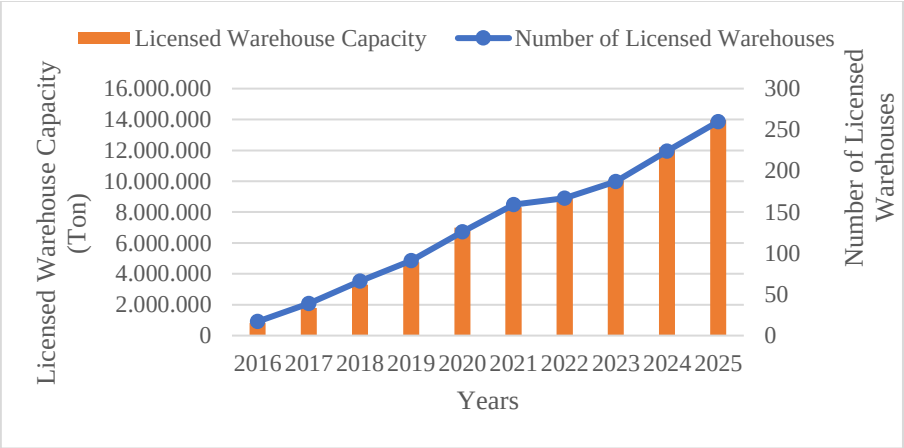
IV. HISTORICAL DEVELOPMENT OF STORAGE SYSTEMS AND LICENSED WAREHOUSING IN TÜRKIYE

In earlier societies, a variety of storage structures such as stone granaries, wooden chambers and rock carved warehouses were constructed to ensure the long term and secure preservation of cereals. A striking example of this practice can be observed in Karaman Taşkale, where two hundred and fifty-one rock granaries carved into a cliff approximately forty meters high during the Roman period have survived to the present day. These structures point to the deep and longstanding history of grain storage in Anatolia. During the Ottoman period, storage infrastructure became progressively more institutionalized. The Derince silo constructed in the year 1897 and the Haydarpaşa silos built between the years 1904 and 1907 by foreign companies represent early examples of grain storage facilities in the modern sense. In Türkiye, the construction of silos began in the second half of the nineteenth century with wooden structures, followed by a transition to brick and concrete silos, and after the year 1950 steel silos became increasingly widespread. This sequence of developments reflects the historical evolution of storage technology (Yıldırım, 2019).

The licensed warehousing system, which represents the institutional form of modern storage practices, was introduced in Türkiye in the year 2010 with the establishment of the first facility created through the partnership of the Turkish Grain Board and the Union of Chambers and Commodity Exchanges of Türkiye (Anonymous, 2025a). The first licensed warehouses were established in Polatlı, Lüleburgaz and Ahi Boz, enabling the storage of oilseeds, cereals and pulses. Licensed warehousing is a system in which agricultural products are stored securely, traceably and with quality control in facilities that meet predetermined technical standards and are subject to regular public oversight. Within this system, an Electronic Warehouse Receipt known as ELUS can be issued for products stored in licensed warehouses. The classification and quality analyses of stored products are conducted in authorized grading laboratories, and the trading of these products can be carried out through national and international commodity exchanges that specialize in agricultural products.

According to recent data, as of September there are 475 warehouse enterprises in Türkiye that hold establishment permits, and 260 of these have obtained operating licenses. The current capacity of licensed warehouses has reached 13.954.999 tons, while the total projected capacity of these enterprises stands at 26.481.009 tons (Anonymous, 2025b). Changes in the number of licensed warehouses and total storage capacity in Türkiye during the period 2016-2025 are presented in Figure 4 (Anonymous, 2025b).

These figures show that storage capacity dedicated to preserving agricultural products through modern warehousing infrastructure has increased rapidly, while also supporting market stability and the effective use of financial instruments in the agricultural sector. Furthermore, 98.6% of establishment capacity is allocated to cereals, pulses and oilseeds, indicating that the licensed warehousing system is heavily concentrated on these fundamental agricultural products. The remaining capacity is allocated to the storage of cotton, dried apricot, hazelnut, dried grape, olive, pistachio, olive oil and dairy products. When all product groups are evaluated together, the conversion rate of establishment capacity into licensed capacity is 52.7% (Table 6).



Şekil 4. Changes in the Number and Capacity of Licensed Warehouses in Türkiye During the Period 2016-2025 (Anonymous, 2025b)

Table 6. Total Establishment Capacity and Total Licensed Capacity by Product Groups (Anonymous, 2025b)

Product Group	**Total İnstalled Capacity**	**Total Licensed Capacity**
Cereals, Pulses and Oilseeds	25.823.980	13.753.470
Cotton	346.000	46.500
Dried Apricots/Grapes, Hazelnuts	203.529	133.529
Olives	63.500	13.500
Pistachios	19.000	4.000
Olive Oil	14.000	**-**
Dairy Products	11.000	4.000
Total	**26.481.009**	**13.954.999**

The data reveal that licensed warehousing capacity in Türkiye exhibits a pronounced concentration across provinces. Konya ranks first, accounting for 16% of the total establishment capacity, indicating that it occupies a central position within the country's storage infrastructure. Diyarbakır follows with a share of 8.7%, while Mardin ranks third with 6.3%. This distribution demonstrates that the Central Anatolia and Southeastern Anatolia regions hold strategic significance within the licensed warehousing system. The fact that licensed warehousing permits have been issued in 53 provinces nationwide indicates that the system has a broad geographical spread, although capacity remains concentrated in a limited number of key provinces. This pattern is likely associated with regional factors such as production structure, investment intensity and the effectiveness of licensing processes (Table 7).

Table 7. Distribution of Total Establishment Capacity and Licensed Warehouse Capacity by Provinces with the Highest Capacities in Türkiye (Anonymous, 2025b)

Provinces	Total İnstalled Capacity	Total Licensed Capacity
1. Konya	4.242.150	2.460.000
2. Diyarbakır	2.330.150	991.630
3. Mardin	1.691.190	739.190
4. Adana	1.607.480	985.030
5. Şanlıurfa	1.329.729	731.779
6. Yozgat	1.288.530	869.575
7. Aksaray	963.850	600.550
8. Tekirdağ	918.120	378.120
9. Eskişehir	803.320	366.320
10. Gaziantep	705.250	418.665

V. THE ELECTRONIC WAREHOUSE RECEIPT (ELUS) MARKET IN THE CEREAL SECTOR

During the period from 2018 to 2024, the transaction volume in licensed warehouses increased by a factor of 24, while the transaction value grew by a factor of 2.6. The sharp rise in transaction volume indicates that the use of the licensed warehousing system has expanded considerably and that the level of adoption among market participants has increased. On the other hand, the more moderate growth in transaction value suggests that the expansion in economic value generation has followed a limited and gradual trajectory. This pattern reveals that although the system has expanded rapidly in quantitative terms, its development in terms of value has remained more measured (Figure 5).

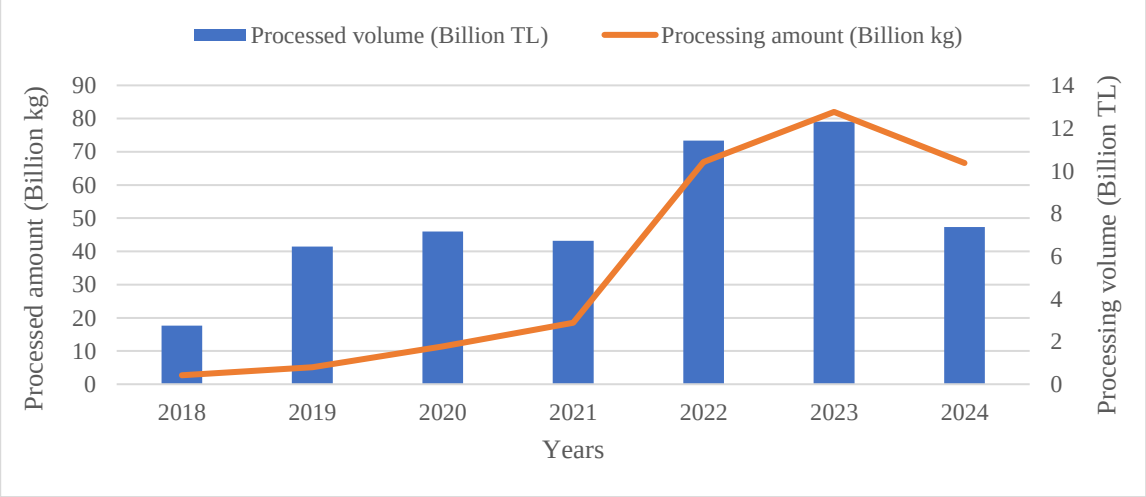


Figure 5. Changes in Transaction Volume and Transaction Value in Licensed Warehouses Between 2018 and 2024 (Anonymous, 2025c)

As of the year 2024, the distribution of transaction value in the Electronic Warehouse Receipt (ELUS) market by product is 54% for wheat, 33% for maize, 7% for barley, 2% for sunflower seed and 1% for other products. In the same year, when transaction volume by product is

examined, wheat ranks first with a total of 3,726,146,165 kilograms, followed by maize with 2,861,419,364 kilograms and barley with 641,655,835 kilograms (Figure 6). These figures indicate a pronounced concentration in both transaction value and transaction volume in the ELUS market, demonstrating that staple agricultural commodities, particularly cereals, continue to dominate market activity.

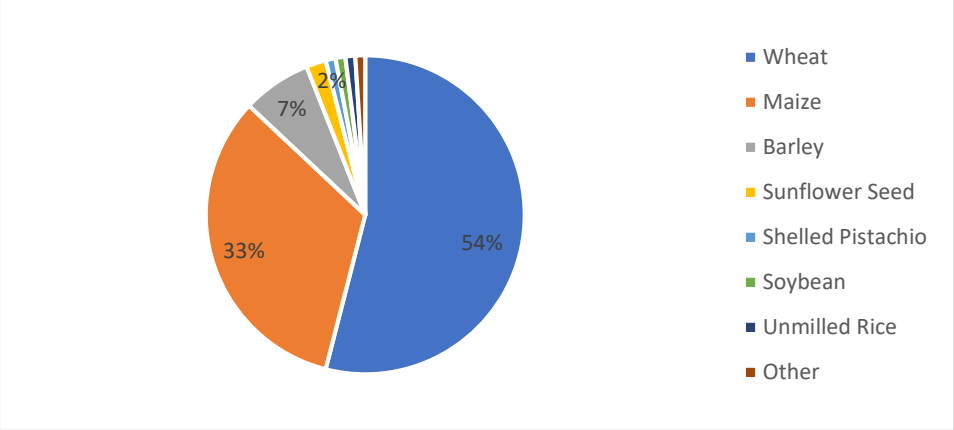


Figure 6. Transaction Value in the ELUS Market by Product in 2024 (Anonymous, 2025d)

VI. CONCLUSION

Cereal production is gaining increasing importance worldwide due to population growth and shifts in consumption patterns. Türkiye's agricultural production capacity holds a strategic position in terms of food security. In this context, modern storage infrastructure and the licensed warehousing system play a vital role in preserving production volumes and reducing post-harvest losses. In recent years, the licensed warehousing system in Türkiye has undergone rapid expansion, contributing significantly to the protection of product quality, the stabilization of prices and the safeguarding of producer incomes through increases in storage capacity. The system also functions as an effective instrument for strategic stockholding, market regulation, loss reduction and transparent trade. Accordingly, licensed warehousing supports Türkiye in maintaining its agricultural production potential and reducing external dependence. As a key component of sustainable agricultural policies, the system is expected to become even stronger in the coming years through further capacity expansion, more balanced regional distribution and the deepening of the Electronic Warehouse Receipt (ELUS) market. Overall, licensed warehousing is not merely an infrastructure development tool but a strategic mechanism positioned at the core of agricultural economics, food security and sustainable production policies. The continued expansion of the system will make substantial contributions to safeguarding Türkiye's agricultural production capacity and reducing reliance on external supply sources.

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REGULATION, SAFETY AND CERTIFICATION ISSUES IN AUTONOMOUS FLIGHTS

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ABSTRACT

Autonomous flight operations, encompassing unmanned and optionally piloted aircraft, offer a new paradigm in today's aviation in terms of operational efficiency, cost optimization, and the reduction of human error. However, this technological transformation, when integrated with existing airspace structures and regulations, brings with it serious regulatory, safety assurance and certification problems. The ability of autonomous systems to make decisions independently of human factors redefines the traditional understanding of "pilot responsibility"; this situation raises new debates at both legal and ethical levels. This study analyses current regulatory efforts undertaken by ICAO, EASA, and the FAA, examining international frameworks developed for the safe and standardized implementation of autonomous flight. Within the scope of the study, regulatory documents, accident and incident data, as well as certification procedures were evaluated; existing bottlenecks in technology validation, human audit, artificial intelligence transparency, and ethical responsibility were identified. The findings demonstrate the critical importance of cybersecurity, software validation, data reliability, and oversight mechanisms for the integration of autonomous systems into the airspace. As a result, in the face of the rapid development of artificial intelligence-based systems, existing aviation legislation needs to be restructured, and certification processes need to be adapted in a dynamic, transparent and ethical manner. This study proposes an integrated regulatory approach at the international level for the safe expansion of autonomous flights.

Keywords: Autonomous flight, certification, regulation, air safety, EASA, FAA, ICAO, AI in aviation

1. Introduction

The gradual merging of autonomous and semi-autonomous systems with the entire ecosystem is one of the most significant changes in technology that has taken place in the aviation sector. The transition of aircraft operations to be fully automated includes drones, UAVs, RPAS, and OPAs, which are all expected to result in better capacity, less operating cost, and reduced human errors among others. By making AI and advanced automation the key factors of decision-making for flight operations, the roles of the pilots and the systems are redefined in terms of the responsibility and accountability.

Nonetheless, the integration of autonomous systems to the current airport infrastructures creates tricky, partial, and hazardous circumstances. The classical takeoff configurations, which were originally based on human-controlled aircraft, are now facing the problem of introducing the systems that are capable of making autonomous decisions. Besides, the absence of unified international regulations for the automation systems adds to the difficulties in the certification, airport integration, and simplification processes.

This paper looks into the current global situation of the market, points out the safety assurance and certification trends, and gives an integrated renewable proposal for the safe rollout of autonomous flight. The focus is primarily on the very first stages of the deployment of autonomous systems, the technological development of that, and the safety management by ICAO, EASA, and the FAA.

2. Literature Review

2.1. Autonomous Flight Technologies

The future of aerial transport will undoubtedly rely upon the combination of advanced automation, AI-based decision-making, detect-and-avoid (DAA) systems, redundant avionics, secure command-and-control (C2), etc. The key features that will define the next-generation Unmanned Aircraft Systems (UAS), Remotely Piloted Aircraft Systems (RPAS), and Urban Air Mobility (UAM) are the very same sensing technologies, meanwhile, ICAO (2020), alongside FAA’s UAS Integration Office (2023), claim that the maturity of the autonomous systems is heavily dependent on the DAA algorithms' reliability, fail-operational redundant flight control architectures, and resilient data links that can sustain integrity under cyber threats.

Research is pointing out the potential of autonomous flying machines to operate in various fields. Some companies, namely Reliable Robotics and Xwing, have developed and tested to an extent an autonomous cargo airliner that is able to perform gate-to-gate automated taxi, takeoff, cruise, and landing (FAA, 2023). It has been found that the use of autonomous flight systems leads to significant improvement in logistics operations, access to the locations where the aircraft's pilot-less design is the only solution, and reduced costs related to the crew (one-third of the total operations cost can be reduced in the case of continuous operation in the 24/7 mode) (Clothier et al., 2019). In the context of public safety and disaster response, autonomous systems are already proving their worth by taking up the role of humans in the dangerous zones where, on the one hand, the human presence would have to be minimized and, on the other hand, the search-and-rescue, wildfire monitoring, and damage assessment missions would be supported (NASA, 2022).

One of the key areas where high-level autonomy is a must is represented by the Urban Air Mobility (UAM) platforms, which are the main application of such technology. EASA (2021) foresees that the UAM operations will be scaled to a much greater extent than just for a limited number of piloted flights, and this will be chiefly due to the airspace complexity and lack of

trained pilots. Airbus (2023) and another study by Boeing/Insitu reveal that autonomy of the aircraft will be the major factor that makes it possible for not just air taxis but also cargo drones to transport and even interact with digital traffic control systems (U-space/UTM) and cooperate with other airspace users across the world even in dense urban areas.

NASA's Aeronautics Research Mission Directorate has conducted studies that confirm and stress that the autonomy would be the key capability for the future air transport and traffic systems. Moreover, the very same document—NASA's Autonomy Strategy for Aeronautics (2022)—declared that futuristic urban air mobility comprising air taxis (AAM), UAM, high-altitude operations, and even robots handling cargo at a distance cannot be realized without an advanced system of onboard autonomy, continuous AI monitoring of the system, and an adaptive flight-deck automation. In like manner, the major players in the market like Airbus and Boeing have also pointed out in their technology roadmaps that autonomy is the main factor concerning the reduction of the operational burden, the enhancement of safety, and allowing airplanes to make contextually aware decisions instantly (Airbus, 2023; Boeing, 2022).

2.2. Regulatory Context

The rapid development of self-flying aircraft has not only boosted but also hastened regulatory measures around the world and mainly the International Civil Aviation Organization, the European Union Aviation Safety Agency, and the Federal Aviation Administration. Each authority has made a lot of progress in policy-making to cope with the issues relating to integration, safety in airspace, and certification routes, but the existing systems can still not support operations that are completely autonomous, particularly those which require making choices through AI.

The International Civil Aviation Organization (ICAO) laid out the basic regulatory framework for Remotely Piloted Aircraft Systems (RPAS) and eventually, unmanned aircraft. The ICAO Manual on Remotely Piloted Aircraft Systems (Doc 10019) contains worldwide directives regarding RPAS licensing, the performance of detect-and-avoid systems, command-and-control (C2) requirements, and international operations (ICAO, 2020). Moreover, ICAO Annexes 6, 2, and 10 have been amended, together with the publications, bearing in mind the necessities of communication, surveillance, and operations to unmanned aircraft.

ICAO published the RPAS Concept of Operations (ConOps) and the UAS Toolkit, which are the basis for cross-border operations and standardized safety assessment methodologies. Nevertheless, ICAO acknowledges that current SARPs (Standards and Recommended Practices) do not cater for high autonomy levels, in which human command is substituted by onboard decision making (ICAO, 2021).

The European Union Aviation Safety Agency (EASA) has put in place one of the most thorough supervisory frameworks for autonomous and highly automated aircraft systems. The U-space Regulation (Regulation (EU) 2021/664) sets out a unified framework for the use of UAVs in low-level airspace through the application of digital traffic management services, such as network identification, geofencing, and dynamic reconfiguration of airspace.

EASA has also made a passing of certification standards:

- SC Light-UAS for advanced unmanned aircraft
- SC-VTOL for eVTOL and air taxi vehicles, including autonomous and optionally piloted aircraft (EASA, 2019)

- AI Roadmap for Aviation (2023) indicating requirements for reliable AI, human supervision, algorithm transparency, and safety assurance

EASA asserts that the certification of AI-based automation under the current prescriptive frameworks like CS-23/CS-27 is impossible without the introduction of new performance-based methodologies (EASA, 2023). They also point out that the traditional DO-178C software requirements are not suitable for machine learning systems.

On the other hand, the U.S. Federal Aviation Administration (FAA) takes a more gradual route. The FAA's regulation known as Part 107 is in charge of small UAS operations while Part 135 exemptions have allowed autonomous cargo operations by companies like Zipline, Wing, Xwing, and Reliable Robotics (FAA, 2023).

The FAA made it possible to use new certification frameworks:

- UAS Type Certification under Part 21
- Reusable Safety Cases for Autonomous Flight
- MOSAIC Rulemaking (Modernization of Special Airworthiness Certification) for future autonomy in light aircraft
- Advice on detect-and-avoid and command-and-control performance according to RTCA DO-365 and DO-377

The FAA, however, concedes that there are substantial regulatory gaps for completely autonomous aircraft, particularly in the areas of human-out-of-the-loop decision-making, AI validation, and remote pilot responsibility (FAA, 2022).

Several unresolved issues, which are present across the ICAO, EASA, and FAA frameworks, include:

- Heterogeneous definitions for autonomy levels
- No consensus on the method for certifying avionics based on machine learning
- Diverse approaches to airspace integration (U-space, UTM, NAS Integration)
- Liability and accountability for AI personified decisions not structured clearly
- Safety models for continuous-learning algorithms are still insufficient

Evidently, the authorities have made enormous regulatory progress but they still admit that the existing aviation law which was originally intended for manned aircraft needs to be completely reformed to allow for higher autonomy levels.

2.3. Safety and Human Factors

Reduced pilot workload is usually mentioned as one of the main advantages of autonomous flight systems, but the literature mentions that the new safety risks for the planes are also considerable which come from the increased use of automation. Cross-sectional studies examining the functioning of a highly automated cockpit demonstrated that the over-reliance on automation could cause "automation complacency" to manifest, and that would result in the effective monitoring performance being lowered and the pilot's reaction to the system failure being accordingly delayed (Parasuraman & Manzey, 2010; FAA, 2022). Research results from the accident and incident investigations, including Air France 447 and Asiana 214, show the diminishing of the situational awareness and the misunderstanding of the automation modes being among the causes that could lead to catastrophic endings (NTSB, 2014; BEA, 2012).

The use of artificial intelligence in deciding matters comes with the extra risk of the non-transparency of the machine-learning models which is usually called the "black-box problem." In the AI Roadmap 2.0 by EASA (2023), it is stated that the absence of transparency in algorithms is a great barrier to certification, safety guarantee, and post-event accountability. The issue is critical in detect-and-avoid systems, adaptive flight control algorithms, and autonomous navigation as the real-time decision processes have to be explainable and traceable for safety supervision.

Another critical safety issue is posed by cybersecurity vulnerabilities. With the extensive utilization of data links, cloud communication services, and remote command systems, autonomous aircraft become susceptible to different types of threats like GPS spoofing, data link jamming, malware injections, and unauthorized access to flight control systems. Both ICAO (2020) and RTCA DO-326A assert that the cybersecurity framework should encompass the entire aircraft life cycle, from design to operation, more so in the case of autonomous systems which need continuous connectivity.

These new risks have led to the human control concept of "meaningful human control" (MHC) to be of great importance in discussions about safety governance related to autonomy. The concept, which was initially expressed mainly in the literature of human-machine interaction (Santoni de Sio & Van den Hoven, 2018), has now reached the discussions of rights in the aviation sector and asserts that humans must always have the ability to watch, intervene and be finally responsible for the important decisions made by the autonomous systems. EASA and ICAO emphasize that the development of autonomy should only serve to increase human power over the machines, and it should never be a straight replacement of the latter, especially in complex or non-nominal conditions.

To summarize, the existing literature agrees on the view that although autonomy can make regular operations safer, different kinds of risks come up from non-transparent AI behavior, cyber security issues, reduction in human situational awareness, and the lessening of the human operator's role. All these concerns demand the application of new verification, validation, and certification methods that are not limited to traditional aviation safety practices but rather encompass them.

3. Methodology

The regulatory, safety, and certification issues concerning the operations of unmanned aerial vehicles are the focus of this study which uses a qualitative document analysis approach. Document analysis is seen as a solid qualitative research method for doing a systematic review and interpretation of policies, regulations, technical standards, and accidents reports (Bowen, 2009). The application of this technique leads to the detection of patterns, regulatory voids, and the rise of topics that reveal the present governance of autonomous flight.

3.1 Data Sources

The main data set is made up of five document groups:

The regulatory documents issued by the ICAO, EASA, and the FAA—namely, ICAO Doc 10019, EASA's AI Roadmap 2.0, and FAA UAS Integration policies—were inspected in order to evaluate the existing regulatory methods, certification necessities, and safety benchmarks for autonomous systems (ICAO, 2020; EASA, 2023; FAA, 2023).

Reports of accident investigations taking place with the help of automation, remote piloting, or autonomy-related factors were analyzed. These consist of significant inquiries like Air France 447 (BEA, 2012), Asiana Airlines 214 (NTSB, 2014), and incidents that are drone-related and

have been recorded in the FAA's UAS accident database and EASA occurrence reports (EASA, 2022).

Evaluated were the documents articulating the certification frameworks for the autonomous and unmanned aircraft—like EASA's SC-VTOL, SC-Light UAS, and RTCA DO-365/DO-377 for detect-and-avoid and C2 links—so as to uncover the existing technological validation and verification limitations (RTCA, 2020; EASA, 2019).

A thorough examination of peer-reviewed articles related to AI interpretability, independent system safety, computer security, and human control that is important to society was conducted so as to fuse ethical and technological viewpoints. Main references are Parasuraman & Manzey (2010), Santoni de Sio & van den Hoven (2018), and various researches in the field of airplane autonomy (Johnson & Patel, 2021; Clothier et al., 2019).

A careful evaluation of comparative studies that focused on the differences among national aviation authorities like ICAO, EASA, and the FAA, was done with the intention of finding inconsistencies, policy bottlenecks, and the challenges of international harmonization (Kopardekar & Prevot, 2020; Thipphavong et al., 2018).

3.2 Analytical Procedure

A thematic coding method was employed in the analysis of the collected documents, following the qualitative research traditions established by Braun and Clarke's (2006) thematic analysis framework. Each document got codes assigned to it that were based on the repeating patterns and the relevant terminology and regulatory language of autonomous flight.

The coding process brought to light five main analytical themes:

- Regulation Gaps: Global regulatory frameworks characterized by inconsistencies, lack of definitions, and incomplete provisions concerning autonomy.
- Safety Assurance Issues: Verification of AI systems, validation of detect-and-avoid algorithms, and cybersecurity vulnerabilities management are the main issues.
- Certification Challenges: The present certification standards (e.g., DO-178C) applied to machine-learning–based avionics prove to be insufficient.
- Ethical and Legal Concerns: Issues related to liability attribution, accountability of AI decisions, and human supervision requirements.
- Technological Bottlenecks: Communication latency, data reliability, redundancy architecture limitations, and explainable AI constraints are among the main factors that restrict progress.

3.3 Reliability, Validity, and Triangulation

In order to enhance the methodological rigor of the study, the use of triangulation was applied by integrating:

- Regulatory documents
- Accident investigation findings
- Certification standards
- Peer-reviewed scientific literature

The credibility and reliability of the findings are thus reinforced by this mixed-document triangulation approach which is in line with the best practices prescribed by Patton (2015) and Bowen (2009).

4. Findings

4.1 Regulatory Challenges

The planetary transition from pilot-centric aviation to machine-based decision-making necessitates a thorough overhaul of the current aviation regulations. The present regulatory regimes—mainly based on the premise of a human pilot-in-command—do not encompass the required provisions for governing the complete autonomy of operations. The ICAO's RPAS Panel and the ICAO Legal Committee (ICAO, 2021) have pointed out that global civil aviation law is still based on the assumption of human accountability, human situational awareness, and human-led decision-making. The use of autonomous aircraft confronts these assumptions at all instances.

The issue of different definitions for autonomy levels is one of the most usually mentioned problems regarding regulations. Although EASA in its AI Roadmap 2.0 (2023) mentions "automation levels," and NASA places autonomy in its Autonomy Levels for UAM/AAM (NASA, 2022), ICAO has not yet recognized or created the same range of terms for levels of autonomy in the airspace as civil aviations have in automobiles using the SAE J3016 standard. Such a situation causes the issuance of varied certifications and different operational approvals in various states (Clothier & Newman, 2020).

Legal scholars point out that the prevailing liability regimes—based on either pilot-in-command or operator supervision—are not capable of dealing with situations where an aircraft's decision-making process is fully machine-based (Finck & Pallas, 2020). The judiciary and the regulatory bodies in the aviation sector are without any precedents for the following questions:

- who bears the responsibility—the producer,
- the airline,
- the application creator,
- or the party developing the AI system.

The EASA Artificial Intelligence Concept Paper observes that the traditional liability regime in case of defective products as well might not be able to cope when the systems are making context-dependent, nondeterministic decisions (EASA, 2021). The ICAO's Legal Committee echoes the same by stating that the current regulations cannot yet deal with AI machines that might change through uninterrupted learning (ICAO, 2021).

The approaches to airspace integration differ greatly from one jurisdiction to another:

Europe (EASA): The U-space framework (Regulation (EU) 2021/664) offers a digital ecosystem of air traffic management, featuring automated deconfliction.

United States (FAA): The FAA adopts a gradual approach leading to full integration into the NAS, based on safety cases instead of complete digital automation throughout the airspace (FAA, 2023).

Japan: Changes in the Civil Aeronautics Act (2022) allow for Level 4 autonomous flights, but only with strict government approval.

Singapore: The Civil Aviation Authority of Singapore (CAAS) has established a national testbed for the use of unmanned air vehicles (UAVs) in urban areas.

The great variations among these regions have the consequences of making it harder to do cross-border and certification recognition agreements. Researchers predict that if there is no harmonization, the regulatory isolation of the autonomous aircraft operators may result in their inability to scale up globally (Kopardekar & Prevot, 2020; Thipphavong et al., 2018).

Presently, ICAO SARPs (Standards and Recommended Practices) do not cover the situation in which humans are minimally or totally absent from the operations. The ICAO Doc 10019 however that provides guidance for RPAS, states that a remote pilot is still responsible for all aspects of the flight. As a result, operations that are completely automated where decisions are made without human intervention are not included in the current regulatory framework (ICAO, 2020).

EASA on its part has made it clear that it is a gap in regulation: its AI Roadmap 2.0 indicates that “no certification framework can ever be valid for an AI system taking safety-critical decisions without human supervision” (EASA, 2023). FAA findings are in line with this point of view, highlighting that the absence of a human controller during the real-time flow of the operation will pose a verification and validation problem that cannot be solved through existing DO-178C or Part 21 certification routes (FAA, 2022).

ICAO has laid down the basis for RPAS regulations, yet none of its present-day regulatory texts—Annex 2 (Rules of the Air), Annex 6 (Operations), and Annex 10 (Communication and Navigation)—are capable of covering the operational requirements, performance standards, or safety justification for:

- unmanned aerial vehicles,
- artificial intelligence decisions at flight-deck during the flight,
- automatic detect-and-avoid systems,
- or non-deterministic navigation with dynamic behavior.

The ICAO Future of Aviation Working Paper (2022) clearly states that the totally autonomous aircrafts “do not fit in the present classifications of aircraft operations” and hence the need for a new global regulatory framework.

4.2 Safety Assurance Issues

Autonomous operations not only bring a radical new set of risks to safety, but also the traditional aviation safety methodologies will not be able to handle these issues completely. One of the most critical issues is the failure of detect-and-avoid (DAA). The research of MIT Lincoln Laboratory and NASA revealed that due to situations such as occluded sensors, poor GPS performance, or very dynamic traffic scenarios, existing DAA algorithms might not work (Kopardekar et al., 2016; Kochenderfer & Chryssanthacopoulos, 2011). In fact even the systems like RTCA DO-365-compliant DAA technologies that are certified, still show performance limitations in the cases of dense urban environments and during rapid airspace conflict geometries (RTCA, 2020).

The use of AI in decision-making is another significant challenge that comes with opacity and it can be considered as the main source of such a problem. When sizing up the situation with EASA's AI Roadmap (2023), it is clear that the lack of transparency in the AI decision-making process has hindered the regulators' efforts to check if the AI decisions are explainable, predictable, and repeatable—these are the main requirements for the aviation certification. On

the other hand, recent investigations point out that AI's unexplainable behavior has been a contributing risk factor in several incidents linked to automation (Johnson & Patel, 2021).

The lack of security in cybersecurity adds to the worries about security issues even more. The full automation of aircraft keeps on exchanging data all the time through command-and-control (C2) links, GNSS signals, and cloud-based air traffic management systems like U-space or UTM and gets really exposed to the threats like GPS spoofing, jamming, man-in-the-middle attacks, and unauthorized access to the autopilot or navigation systems. The International Civil Aviation Organization (ICAO) report in 2020 and the European Union Aviation Safety Agency (EASA) guidelines on cybersecurity from 2021 have marked unmanned and autonomous systems as high-risk targets because of their heavy reliance on wireless communication. In fact, the incidents in 2019 where drones were reportedly spoofed in the Black Sea and the Middle East are just some of the real-world cases showing the operational impact of such attacks on navigation (Humphreys, 2013; C4ADS, 2019).

Significant risks are also posed by data integrity and sensor reliability problems. The operation of autonomous planes is based on the combined data coming from different sources like GNSS, IMUs, LIDAR, radar, ADS-B, and vision systems. The study conducted by NASA Armstrong Flight Research Center found that even a slight time-drift in data, loss of sensor packets, or unsynchronized sensor fusion could bring about flight-critical errors in the AI models used for decision-making (NASA, 2022). A similar problem is also being faced at the FAA UAS test areas, and one of the major causes in this case is the environmental conditions such as fog, rain, and electromagnetic interference that result in reduced sensor reliability (FAA, 2023).

The most difficult safety problem seems to be unpredictable system behavior in non-nominal or edge-case scenarios. Traditional avionics are deterministic while AI-enabled systems can respond unpredictably when encountering rare or out-of-distribution events. Research has shown that reinforcement learning-based flight controllers may demonstrate unsafe or unstable reactions when encountering unforeseen stimuli not present in their training datasets (Berquand et al., 2021). This unpredictability presents certification hurdles since regulators are required to show that the system will behave safely in all operational scenarios, a condition that is presently at odds with the variability of machine learning.

In light of these new risks, the top aviation authorities and safety researchers arrive at the same conclusion that classic safety assessment methods FMEA, Fault Hazard Assessment (FHA), and Bow-Tie analysis are not enough for the non-deterministic AI-driven systems (EASA, 2021; ICAO, 2022). However, safety barriers comprising of assurance cases, continuous monitoring frameworks, real-time risk assessment, and explainable AI (XAI) techniques are the only ones that can guarantee safety during the entire lifecycle of the system.

4.3 Certification Limitations

Certification authorities face considerable difficulties in the approval of autonomous and AI-based aviation systems, mainly due to the restrictions of current regulatory frameworks and the use of conventional software assurance techniques. Standardized testing and validation procedures for AI-driven systems are one of the most significant gaps that have been communicated widely. The traditional airworthiness software certification process is controlled by the DO-178C, DO-254, and DO-330 standards, which treat software as deterministic and rule-based. On the other hand, the behavior of machine-learning systems is non-deterministic and they cannot be validated through the same structural coverage and formal verification techniques (RTCA/EUROCAE, 2011; EASA, 2021). Thus, it cannot be assured that the

systems would behave predictably in all the operating conditions, which is a prerequisite declared by the airworthiness regulations themselves.

A major hurdle to overcome is the problem of verification of machine learning models and in particular those for anomaly detection, adaptive flight control, vision-based navigation and detect-and-avoid systems. Because machine-learning models are constantly updating their internal parameters according to the training data, they cannot be validated or certified through the traditional methods of traceability. A joint study conducted by MITRE and FAA (2022) explicitly states the case that ML models are not able to comply with the DO-178C requirement for complete requirements-based verification, thus making them incompatible with the existing certification pathways unless new assurance frameworks are put in place.

Moreover, the autonomous systems will need continuous software assurance, which is different from the static certification model that is employed for conventional avionics. The AI systems, for example, may require retraining or updating from time to time in order to keep up with the changes in their operational environment, thus maintaining their performance. According to NASA (2022) and EASA (2023), continuous-learning or periodically updated algorithms are indeed violating the "frozen software baseline" assumption of DO-178C. Consequently, this forms a regulatory paradox, since the updated ML models would in principle necessitate a new certification cycle after each training iteration.

The lack of metrics for certification based on performance being the major constraint for the autonomous behavior is another constraint. The FAA and EASA agree that prescriptive rule-based certification which is based on deterministic logic cannot assess the probabilistic, adaptive, and context-dependent behavior of autonomous systems (FAA, 2023; EASA, 2023). Researchers propose developing new performance-based methods, assurance cases (Bowen et al., 2020), operational safety envelopes, and scenario-based testing structures that would allow testing similar to those being developed in automobile autonomy (UNECE WP.29).

One of the major obstacles still facing the industry is the validation of autonomous detect-and-avoid (DAA) capabilities. While RTCA DO-365 fixed minimum measurements for DAA systems, these measurements were designed for Part 91/Part 107 drone flights rather than for self-flying drones in controlled airspace or at the same height as commercial aviation (RTCA, 2020). NASA Ames study reveals that DAA algorithms have in the future struggle in high-density traffic, complex geometries, multi-threat conflict scenarios, and degraded sensor environments (Kopardekar et al., 2016).

Regulatory actions like EASA's SC-VTOL (2019), SC-Light-UAS, and the FAA's Type Certification for drones under Part 21 are significant moves in the early phase of certifying autonomous systems. However, the two agencies point out that these special conditions only apply to low-mass, limited-scope operations, and thus do not yet offer a certification route for large, fully autonomous passenger aircraft (EASA, 2019; FAA, 2022).

In general, certification organizations encounter a fundamental problem: the certification concept employed for conventional avionics—grounded on determinism, traceability, and static requirements—cannot be transferred to the case of machine-learning-based autonomy. Therefore, new certification frameworks need to be created that will accept and support probabilistic behavior, AI interpretability, continuous updates, and scenario-based testing.

4.4 Ethical and Legal Dimensions

One of the most difficult and unresolved issues in the governance of aviation today is the ethical and legal questions which are still surrounding the use of autonomous aircraft. The gradual

takeover by AI-based systems of tasks that human pilots usually do raises doubts about who is responsible, who should be accountable, who should provide a clear view, and who has the right to decide among others. In particular, the situation under which a plane is completely flown by machines and humans may not be in control at any time, entails the raising of ethical issues that are outside the scope of existing aviation regulations to handle (ICAO, 2021).

The paramount legal question is actually the one who is to blame in case an autonomous aircraft inflicts harm. In the present scenario of ICAO Annexes and national aviation laws, the "pilot-in-command" (PIC) is the one who holds legal responsibility for all safety-critical decisions taken. Nevertheless, this legal framework disintegrates when the decision-making process is conducted by AI systems installed on the aircraft rather than by a human pilot. According to legal experts, the present liability structures—anchored in negligence, operator supervision, and human mistake—are totally inadequate for AI-sourced choices, particularly those derived from stochastic machine-learning models (Finck & Pallas, 2020; Vladeck, 2014).

EASA (2021) ascertains that during autonomous operations, responsibility might be assigned to different parties:

- the aircraft's manufacturer,
- AI algorithm developers,
- system integrators,
- operators or remote supervisors,
- data service providers located on the ground,
- or all these parties together.

The lack of definite international standards is a major source of concern regarding the disparate interpretations of liability that may occur in different jurisdictions.

A major issue from an ethical standpoint is to guarantee that AI-related decisions will have all the necessary attributes of being transparent, fair, and accountable. AI models employed in various domains of navigation, collision avoidance, and emergency response are often still "black-box" systems from which even the developers cannot infer the internal reasoning. EASA's AI Roadmap 2.0 (2023) underlines a point that "lack of explainability" is the major factor that impedes safety assurance, certification, and post-incident investigation. Likewise, the European Commission's trustworthy AI guidelines issued in 2019 also ask for algorithm transparency as a prerequisite for accountability.

Research indicates that non-transparent AI systems can yield:

- decision-making biased against certain groups in the allocation of emergency services (Danks & London, 2017),
- behavior of the system being unpredictable in the case of rare situations happening ("edge cases"),
- and difficulties with the acceptance of the system by the regulating authorities.

These issues are present to a much greater extent in aviation since safety-critical decision-making has to be totally transparent not only to regulators but also to the airline companies and investigators.

One more major ethical issue is that of deciding the right amount of human intervention. Scholars advocate for the concept of "meaningful human control" (MHC) as a must-have, a

term that was first created in the domain of robotics ethics (Santoni de Sio & van den Hoven, 2018) but is now commonly used in discussions on aviation autonomy. ICAO and EASA are the first regulatory bodies to consider MHC concepts in their viewpoints and to accept that humans must have the final say even when AI systems perform actions that are completely autonomous.

But, the question of "meaningful" control is still very vague. The issues in the debates are:

- Should humans be “in-the-loop”, “on-the-loop”, or totally out of the day-to-day command?
- How fast should humans be able to react for their control to be considered meaningful?
- Can a remote supervisor who has many planes under his command be aware of the situation well enough?

According to NASA studies on the supervision of control, people who are in charge of autonomous aircraft have their ability to perceive the situation correctly reduced and their reaction time lengthened, particularly, if they are monitoring more than one system (Johnson et al., 2021). Such results prompt the question whether it is right to depend on supervision from afar so much that it becomes the only model.

Unmanned airplanes are also raising issues regarding international jurisdiction. The existing International Civil Aviation Organization (ICAO) regulations assume the following presumptions:

- one state of registry,
- a pilot-in-command (PIC) with legal power,
- and a single chain of accountability.

However, the case of fully automated operations—particularly when relying on cloud-based navigation, remote data services, and cross-border digital communication—implies a multi-jurisdictional scenario of shared responsibility. For instance:

- The plane might be registered in Country A,
- The business which operates the plane might be in Country B,
- The data processing centre might be in Country C,
- And the plane might be flying over Countries D and E.

According to the ICAO’s Legal Committee (2021), there is no international agreement at present to identify the responsible party in case of AI-related decision-making spanning across various jurisdictions. The issues of illegal access to data or malfunctioning of cloud-based AI particularly reveal these legal uncertainties.

The change in the definition of the “pilot-in-command” is especially significant for optionally piloted or entirely automated aircraft. Regulations of both FAA and EASA still insist on the appointment of a human commanding pilot for each flight, even when AI controls the flight-critical operations. Notwithstanding, scholarly articles advocate that the duties of the PIC—such as keeping the situation under control, making decisions and reacting fast—cannot be completely entrusted to a distant human supervisor (Barnhart et al., 2021).

This implies a very serious legal dilemma:

- Will an AI system be regarded as a “co-pilot” or an “operator”?

- In case an AI opts for a course of action on its own, will the PIC still be held accountable?
- Is it necessary to come up with new legal frameworks, for instance "System-in-Command" (SIC)?

In its 2022 report on the Future of Air Mobility, ICAO presents the scenario where autonomy comes with a need for the sharing of the PIC concept between humans and AI, thus leading to a complete overhaul of the aviation law with the hybrid model—a radical shift from the traditional legal standards in aviation.

5. Discussion

The evidence points to the necessity for a new regulatory mindset that tolerates independence. The fast development of AI is testing the limits of current aviation legislation. The law makers of the coming days must set forth:

AI transparency requirements (machines that explain and do not hide their decisions)

Dynamic certification models that integrate regular oversight and updating after certification

Cyber-resilient systems with multiple shields of security

Communication paths that are backup so command can be assured

Using the performance-based method instead of prescribing rules

Besides, the human control that has significance should still be the main factor for safety even when the degree of freedom is high.

A globally accepted regulatory framework will be of paramount importance in the avoidance of the fragmented approaches that are not only hindering but also making the global operations difficult.

6. Conclusion and Recommendations

The future of aviation will be determined by autonomous flight operations, as they will not only boost up efficiency but also minimize human mistakes. Still, if there are no strong regulatory, safety, and certification frameworks in place, the risks involved in the implementation of autonomy might overtake the advantages.

The key recommendations are:

- Work out a set of globally harmonized autonomy regulations with the help of synchronized collaboration among ICAO, EASA, and FAA.
- Create certification frameworks for AI that are specific to the technology with clear testing, validation, and explainability requirements.
- Incorporate cybersecurity requirements in all phases of aircraft certification and operation.
- Install ongoing safety monitoring systems for AI-based capabilities.
- Revise legal liability frameworks for autonomous decision-making.
- Encourage the application of ethical governance principles that guarantee the results of fairness, accountability, and transparency.

An integrated international regulatory mechanism is a prerequisite to offset the deployment of autonomous flights with safety and scalability.

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STEREOLİTOGRAFİ (SLA) METODUYLA YAPILAN HIZLI PROTOTİPLEME İŞLEMLERİNDE İŞ SAĞLIĞI VE GÜVENLİĞİ

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ÖZET

Stereolitografi (SLA), hızlı prototipleme teknolojileri arasında yüksek çözünürlükte parça üretimi, mükemmel yüzey kalitesi ve geniş malzeme yelpazesi ile öne çıkan bir yöntemdir. Ancak, bu teknolojinin endüstriyel ve ofis tabanlı kullanımının hızla yaygınlaşması, önemli iş sağlığı ve güvenliği (İSG) risklerini de beraberinde getirmiştir. Bu bildirinin temel amacı, SLA teknolojisinin çalışma prensibi kısaca açıklandıktan sonra, prosesin her adımında ortaya çıkan riskleri sistematik olarak sınıflandırmak ve bu risklere yönelik alınabilecek önlemleri bir literatür taraması ışığında tartışmaktır. Yapılan incelemeler; risklerin başlıca kimyasal, fiziksel ve ergonomik kategorilerde toplandığını göstermiştir. Kimyasal riskler, kürlenmemiş fotopolimer reçinelerin içerdiği kimyasalların neden olduğu cilt tahrişleri, alerjik reaksiyonlar ve solunum yolu irritasyonları şeklindedir. Ayrıca, temizleme aşamasında yaygın olarak kullanılan izopropil alkol (IPA) gibi yanıcı çözücüler, hem yangın riski oluşturmakta hem de solunum sistemine zararlı buharlar yaymaktadır. Proses sırasında ortama salınan uçucu organik bileşikler (UOB'ler) ve ultra ince partiküller de hava kalitesi üzerinde olumsuz bir etki yapabilmektedir. Fiziksel riskler arasında ise ultraviyole (UV) ışınımına bağlı göz hasarları, elektrik çarpması ve mekanik yaralanmalar sayılabilir. Bu riskleri azaltmak için, hiyerarşik bir kontrol yaklaşımı önerilmektedir. En etkin yöntem, tehlikenin kaynağında kontrolünü sağlayan mühendislik kontrolleridir. Bunların başında yazıcıyı kapalı bir kabin içine alarak egzoz sistemi ile buhar ve partikülleri ortamdan uzaklaştırmak gelir. İdari kontroller kapsamında operatörlere kapsamlı eğitim, güvenli çalışma talimatları ve acil durum prosedürlerinin sağlanması kritiktir. Son olarak; kimyasallara dayanıklı nitril eldivenler, koruyucu gözlük ve uygun havalandırmanın olmadığı durumlarda solunum koruyucular gibi kişisel koruyucu donanım (KKD) kullanımı şarttır. Sonuç olarak, SLA teknolojisinden sağlıklı ve güvenli bir şekilde faydalanabilmek için, SLA'nın beraberinde getirdiği ve bu çalışmada anılan risk faktörlerini tanımak ve uygun İSG uygulamalarını hayata geçirmek; gelecekte oluşabilecek iş kazası ve meslek hastalıklarının önlenmesine ciddi katkı sunacaktır.

Anahtar Kelimeler: İş Sağlığı ve Güvenliği, Stereolitografi, Hızlı Prototipleme, Eklemeli İmalat.

OCCUPATIONAL HEALTH AND SAFETY IN RAPID PROTOTYPING PROCESSES USING THE STEREOLITHOGRAPHY (SLA) METHOD

ABSTRACT

Stereolithography (SLA) stands out among rapid prototyping technologies for its high-resolution part production, excellent surface quality, and wide range of materials. However, the rapid expansion of this technology in industrial and office-based use has also brought significant occupational health and safety (OHS) risks. The main objective of this report is to briefly explain the operating principle of SLA, systematically classify the risks in each step of the process, and discuss possible measures to address these risks based on a literature review. Analysis has shown that risks fall primarily into chemical, physical, and ergonomic categories. Chemical risks include skin irritation, allergic reactions, and respiratory irritation caused by chemicals contained in uncured photopolymer resins. Furthermore, flammable solvents such as isopropyl alcohol (IPA), commonly used in the cleaning phase, pose a fire risk and emit vapors harmful to the respiratory system. Volatile organic compounds (VOCs) and ultrafine particles released into the environment during the process can also negatively impact air quality. Physical risks include eye damage from ultraviolet (UV) radiation, electric shock, and mechanical injuries. A hierarchical control approach is recommended to reduce these risks. The most effective method is engineering controls that control the hazard at its source. Chief among these is enclosing the printer in a closed cabinet and removing vapors and particles with an exhaust system. Providing comprehensive training, safe work instructions, and emergency procedures for operators is critical within administrative controls. Finally, the use of personal protective equipment (PPE), such as chemical-resistant nitrile gloves, safety goggles and respiratory protection (in the absence of proper ventilation) is essential. In conclusion, to utilize SLA technology healthily and safely, recognizing the risk factors associated with SLA and the ones mentioned in this study and implementing appropriate OHS practices will significantly contribute to the prevention of future occupational accidents and occupational diseases.

Keywords: Occupational Health and Safety, Stereolithography, Rapid Prototyping, Additive Manufacturing.

1. INTRODUCTION

In todays digitalized production processes, additive manufacturing technologies have become an indispensable tool in many industries, particularly aerospace, automotive, medical, jewelry, and dentistry, thanks to the design freedom they offer compared to traditional production methods, the ability to produce complex geometries, and rapid prototyping capabilities (Gibson, Rosen, & Stucker, 2015). Stereolithography (SLA), the historical pioneer and one of the most widely used types of these technologies, was patented by Chuck Hull in 1986 and is based on the principle of layer-by-layer solidification of a liquid photopolymer resin pool with a laser (Hull, 1986). SLA, thanks to its high surface quality, excellent detail resolution, and a wide range of resin products with controllable mechanical properties, has a wide range of applications, ranging from precision prototyping to the manufacture of personalized products such as medical implants and hearing aids (Liaw & Gu, 2019). However, the proliferation of this technology across businesses of all sizes, including office environments, has raised significant occupational health and safety (OHS) concerns. Although the places where SLA printers used are traditionally considered as low-risk places, they can still expose operators to chemical, physical, and ergonomic hazards (Floyd, Van Dijck, & Stapleton, 2022). Uncured photopolymer resins, in particular, can cause irritation and allergic reactions upon skin contact due to the acrylate-based monomers they contain, and respiratory irritation and systemic effects upon inhalation of their vapors (Zontek, O'Brien, Jankovic, & Hollenbeck, 2017). Furthermore, flammable solvents (e.g., isopropyl alcohol) commonly used in post-printing processes pose a fire risk. Additionally, volatile organic compounds (VOCs) and ultrafine particles released into the environment during the process negatively impact indoor air quality (Stephens, Azimi, El Orch, & Ramos, 2013; Afshar-Mohajer, Wu, Ladun, Rajon, & Huang, 2015).

Therefore, the main objective of this report is to present the basic operating principle of SLA technology, then analyze the OHS risks that can be systematically identified at all stages of the process (e.g., resin preparation, printing, cleaning, final curing) based on a literature review, and comprehensively present the measures that can be taken against these risks in accordance with the hierarchical control principle (elimination, substitution, engineering controls, administrative controls, and Personal Protective Equipment - PPE). This study aims to emphasize that effective and sustainable utilization of SLA technology is only possible with an approach that prioritizes human health and safety.

2. THE WORKING PRINCIPLE OF THE STEREOLITHOGRAPHY (SLA) METHOD

Stereolithography (SLA) is a photopolymerization process that combines the fundamental principle of additive manufacturing—building a 3D object layer by layer from computer-aided design (CAD) data—with the principles of photochemistry (Gibson, Rosen, & Stucker, 2015). This method relies on the selective solidification of a liquid photopolymer resin with a light source of a specific wavelength (usually a 355 nm laser or 405 nm LED). The basic components and operating cycle of the SLA system are detailed below.

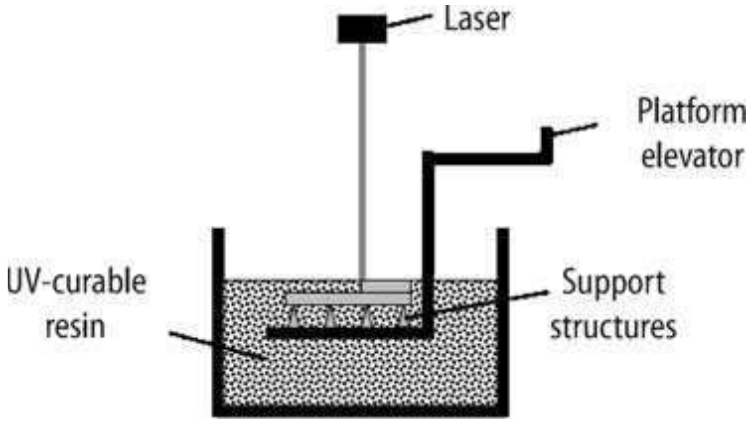

Figure 2.1. How the SLA System Works (Raja, V. & Fernandes, K. J., 2007).

2.1. Basic Components of the SLA System

Resin Chamber (Vat): This is the chamber containing the photopolymer resin. Especially in the "Bottom-Up" configuration, the chamber bottom consists of a transparent silicone-based film (usually FEP - Fluoroethylene Propylene or PDMS - Polydimethylsiloxane) that transmits UV light and allows the solidified resin to be easily separated (Chartrain, Williams, & Whittington, 2018). This film transmits the laser or projector light to the resin while also preventing the layers from adhering to the chamber bottom. Similarly, in the top-down configuration, the resin is contained within this chamber.

Build Platform: In top-down configuration, it is the plate on which the part is built, capable of moving in the vertical direction. In the initial position, the platform is located one layer thick (usually 25-100 microns) below the chamber surface. The resin is deposited on the platform in a thin film. The platform gradually moves downward along the Z-axis at the end of each layer, creating space for the next layer.

UV Light Source and Scanning System: There are two basic configurations:

- **Laser-Based SLA (Vat Polymerization):** In this system, a high-power UV laser (e.g., a 355 nm Solid State Laser) is controlled by a system of two mirrors called "galvanometers" that move along the X and Y axes. The galvanometers precisely scan the laser spot across the resin surface, drawing the cross-sectional contour of each layer (Moghadam, Kamrani, & Ertas, 2021).

- **Digital Light Processing (DLP):** This method utilizes a UV LED light source and a Digital Micromirror Device (DMD). A DMD consists of thousands of microscopic mirrors, each corresponding to a pixel. This device processes a cross-sectional image of each layer by simultaneously exposing (curing) the entire layer as an "image," rather than using a laser's point-by-point scanning technique (Liaw & Gu, 2019). This generally makes DLP faster than laser-based SLA.

Control Software: Takes a CAD model (STL or 3MF file) and divides it into horizontal sections (layers). For each layer, the software generates the laser scan path (hatching and border strategies) or the digital mask for the DLP projector. It also controls platform movement, exposure times, and other machine parameters.

2.2. How the SLA Process Works

The SLA process can be broadly described as pre-processing (preparing the CAD model, preparing the printer and resin for printing), printing (layering and exposure, separation,

repeating the process for each layer), and post-processing (cleaning, final curing). These steps of the SLA process are explained below.

1. **Model Preparation and Slicing:** The CAD model is prepared and sliced in SLA software, adding support structures. Support structures are critical for supporting the overhangs and connecting the part to the platform.

2. **Layer Creation and Exposure:** The platform is lowered one layer below the chamber surface, allowing a thin layer of liquid resin to be deposited on the platform. The UV light source is activated. In a laser-based system, the laser is directed by galvanometers and scans the cross-sectional shape of the layer. The exposed resin undergoes a polymerization reaction, solidifying and chemically bonding to the platform or the previous layer. In a DLP system, the image of the entire layer is simultaneously projected onto the resin layer, ensuring simultaneous solidification.

3. **Repeat Cycle:** The platform is repositioned for the next layer (i.e., lowered one layer thickness into the uncured resin), and the resin on the surface fills the vacated area using a recoater or gravity. The blade scrapes the surface smoothly to ensure a smooth surface and removes any bubbles on the resin surface. Steps 2 and 3 are repeated until the entire part is created.

4. **Post-Processing:** Once printing is complete, the platform is removed from the resin chamber and the excess resin is allowed to drain. The part is then washed in an organic solvent (usually isopropyl alcohol - IPA) to remove any remaining uncured resin. Support structures are mechanically removed (usually by hand), and finally, the part is "post-cured," usually in a UV oven, to improve the part's mechanical properties and chemical stability. This post-curing process ensures that any monomers not fully reacted during printing fully polymerize and the part achieves the desired rigidity. This detailed process allows us to understand why SLA is suitable for delicate and complex parts, but also poses OHS risks due to chemical use and mechanical processes.

3. HEALTH AND SAFETY RISKS IN SLA PROCEDURES

3.1. Chemical Risks

Chemical exposure is the most dominant and well-documented risk factor in SLA procedures. This includes photopolymer resins, solvents used for cleaning, and the volatile organic compounds that may be released into the environment during their use.

Photopolymer Resins: SLA resins contain acrylate and methacrylate based monomers and oligomers that solidify by cross-linking with UV light. In their uncured state, these substances can cause skin irritation, contact dermatitis, and allergic reactions (Liaw & Gu, 2019). Inhalation of resin vapors can cause health problems such as headache, dizziness, nausea, and respiratory irritation (Zontek et al., 2017). Azizoglu, Birch, and Tüzün (2020) reported that more than 75% of the resins they examined carried irritant warnings for the skin and respiratory system.

Cleaning Solvents: Isopropyl alcohol (IPA), commonly used for cleaning parts, is highly flammable, and its vapors can irritate the respiratory tract, cause headaches, and nausea (Afshar-Mohajer, Wu, Ladun, Rajon, & Huang, 2015). Prolonged or high-dose exposure can affect the central nervous system.

Volatile Organic Compound (VOC) Emissions: VOCs are released into the environment during the printing and cleaning processes. Stephens et al. (2013) found that VOC concentrations emitted from SLA printers are generally higher than those from fused deposition

modeling (FDM) printers and can exceed office air quality standards. These emissions have also been linked to the formation of particulate matter (Gu, Greenspan, & Chou, 2020).

3.2. Physical Risks

UV Radiation: UV light sources (lasers or high-power UV LEDs) from SLA printers can cause retinal damage if exposed directly to the eye (Moghadam, Kamrani, & Ertas, 2021). While most modern devices have enclosed housings and UV-blocking covers, this risk may occur during maintenance or intervention. The same exposure risk may also exist for UV ovens which are used for final curing.

Fire and Explosion Risk: The presence of flammable liquids (resin, IPA) poses a fire risk due to electrical faults, overheating, or sparks from static electricity (Kim, Kim, & Yeom, 2019). IPA vapor, in particular, is heavier than air and can accumulate in enclosed spaces, creating an explosive atmosphere.

Electric Shock: Printers with high voltage components (UV light source, heaters) present a risk of electric shock in the event of improper use or grounding fault.

Mechanical Risks: The moving platform and other mechanical parts may pose a risk of compression, especially during maintenance.

3.3. Ergonomic and Other Risks

Manipulation and Repetitive Tasks: Finishing operations such as removal of support structures, sanding, and cleaning may require repetitive hand movements and working in awkward positions, which may cause to musculoskeletal disorders (European Agency for Safety and Health at Work [EU-OSHA], 2019).

Waste Management: Used resin, deteriorated solvents, and contaminated cleaning materials can be classified as hazardous waste. Failure to properly dispose of these wastes can lead to environmental pollution and, indirectly, health risks (Larson, 2021).

In addition to those given above, a summary table from the literature expressing the risks arising in the SLA system along with the process stages is presented in Table 3.1. below.

Table 3.1. Hazards and Potential Impacts by SLA Process Stages

Process Step	Major Hazards	Potential Health/Safety Impacts	References
Resin Filling/Transporting	Liquid resin contact, spillage	Skin irritation, allergies, risk of slipping	Liaw & Gu (2019); Zontek et al. (2017)
Printing	Resin vapors (VOCs), UV radiation, electricity	Respiratory problems, eye damage, electric shock	Stephens et al. (2013); Gu et al. (2020)
Cleaning (with IPA)	Solvent vapors, flammability, contact	Respiratory irritation, narcotic effect, fire/explosion	Afshar-Mohajer et al. (2015); Kim et al. (2019)
Support Removal/Sanding	Mechanical stress, particle formation	Musculoskeletal disorders, respiratory tract irritation	EU-OSHA (2019)
Final Curing	UV radiation, residual vapor from the resin	Eye damage, respiratory irritation	Moghadam et al. (2021)

4. RESULTS

The results include the precautions and safe working conditions. A hierarchical control approach (elimination, substitution, engineering controls, administrative controls, and Personal Protective Equipment - PPE) should be adopted to manage risks (National Institute for Occupational Safety and Health [NIOSH], 2022). Thus safe & healthy working conditions will be ensured.

4.1. Engineering Controls

Local Exhaust Ventilation: SLA printers should be housed in an enclosed cabinet, and this cabinet should be equipped with a local exhaust ventilation system that removes contaminated air to the outside environment or a filter system. This is the most effective way to control chemical exposure (Zontek et al., 2017).

Closed System Design: The printer should preferably have a sealed and automatic design that protects the operator from UV radiation and resin vapors.

Room Ventilation: Good general ventilation should be ensured in the room where the SLA procedure is performed.

4.2. Administrative Controls

Training and Awareness: All operators must be trained on the material safety data sheets of the chemicals used, the safe use of equipment, and emergency procedures (OSHA, 2012).

Marking and Labeling: All hazardous chemicals and equipment must be appropriately marked and hazardous areas must be designated.

Safe Working Procedures: Written procedures should be established for resin filling, cleaning, and maintenance operations. Marked areas where eating/drinking are prohibited should be established.

Emergency Plan: The steps to be followed in case of chemical spill, fire or injury should be determined and personnel should be trained on this subject.

Health Surveillance: Regular health screenings can be beneficial, especially for respiratory and skin problems.

4.3. Personal Protective Equipment (PPE)

The use of PPE should be used as a last line of defense after the other measures listed above have been implemented.

Gloves: Chemical-resistant nitrile gloves should be used; latex gloves should not be preferred as they do not provide sufficient protection (Azizoglu et al., 2020).

Safety Glasses: Safety glasses are used to protect eyes against the liquid splashes and even vapor exposure.

Lab Coat: Should be used to protect the body and clothing from chemicals.

Respiratory Protection: In cases where ventilation is inadequate or especially in high-risk operations (IPA pouring, cabin cleaning), organic vapor filter masks (above FFP2/N95) should be used (NIOSH, 2022).

5. CONCLUSION

SLA technology, with the advantages it offers, will continue to play an indispensable role in production processes. However, for this technology to be used sustainably and safely, it is

essential to acknowledge and proactively manage the associated OHS risks. Literature review indicates that these risks are particularly concentrated around chemical exposure and fire. In this context, the following recommendations can be offered:

- SLA processes should be located in controlled laboratory or workshop environments rather than office environments.
- SLA printers should not be operated without local exhaust ventilation.
- Operator training and awareness should be central to safety culture.
- Manufacturers should be encouraged to develop "environmentally friendly" resins with lower toxicity and to design safer, fully enclosed systems.
- Studies should be initiated in our country (Turkiye) to develop OHS regulations and guidance documents specific to additive manufacturing technologies.

Only in this way, the health and safety of employees can be effectively protected while maximizing the innovative potential brought by SLA technology.

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KAPALI/ DİKEY BİTKİSEL ÜRETİMDE IŞIK VE ENERJİ YÖNETİMİ: YAPAY ZEKÂ TABANLI OPTİMİZASYON STRATEJİLERİ

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ÖZET

Küresel nüfus artışı, kentleşme ve iklim değişikliğinin geleneksel tarım üzerindeki baskıları, kapalı ve dikey bitkisel üretim sistemleri gibi yenilikçi yaklaşımları gıda güvenliği ve sürdürülebilirlik için kritik hale getirmiştir. Bu sistemler alan, su ve toprak kullanımında yüksek verimlilik sunsa da, özellikle yapay aydınlatma ve iklimlendirmeden kaynaklanan yüksek enerji tüketimi, ekonomik fizibiliteyi ve çevresel sürdürülebilirliği olumsuz etkilemektedir. Bu derleme makalesi, KVBÜS'lerde ışık ve enerji yönetiminin optimizasyonunda yapay zekâ tabanlı stratejilerin rolünü teknik ve analitik bir yaklaşımla incelemektedir. Makale, fotosentez ve bitki morfolojisi üzerindeki spektral etkileşimlerden enerji verimli LED teknolojilerinin dinamik kontrolüne ve HVAC sistemlerinin akıllı yönetimine kadar YZ'nin dönüştürücü potansiyelini ele almaktadır. Makine öğrenimi, derin öğrenme ve pekiştirmeli öğrenme gibi YZ algoritmaları, bitki büyümesini maksimize ederken enerji tüketimini ve operasyonel maliyetleri minimize eden adaptif ve özerk kontrol stratejilerinin geliştirilmesine olanak tanımaktadır. Spektral optimizasyon, dinamik ışık rejimleri, tahmine dayalı iklim kontrolü ve bitki fizyolojisi tahminleri gibi YZ uygulamaları, KVBÜS'ün verimliliğini, mahsul kalitesini ve sürdürülebilirliğini artırmaktadır. Ancak, yüksek başlangıç maliyetleri, veri yönetimi zorlukları, uzman personel eksikliği ve etik kaygılar gibi önemli engeller bulunmaktadır. Gelecekteki araştırmaların yenilenebilir enerji entegrasyonu, daha kapsamlı veri altyapıları, ileri düzey algoritmalar ve modüler sistem tasarımları aracılığıyla bu zorlukların üstesinden gelerek YZ tabanlı KVBÜS çözümlerinin etkinliğini ve erişilebilirliğini artıracağı vurgulanmaktadır. YZ'nin KVBÜS'leri daha verimli, ekonomik ve sürdürülebilir hale getirerek tarımın geleceğinde devrim yaratma potansiyeli olduğu sonucuna varılmıştır.

Anahtar Kelimeler: Kapalı Bitkisel Üretim, Dikey Tarım, Yapay Zekâ, Işık Yönetimi, Enerji Optimizasyonu, Makine Öğrenimi, Pekiştirmeli Öğrenme, Sürdürülebilir Tarım, Kontrollü Çevre Tarımı, Akıllı Tarım.

LIGHT AND ENERGY MANAGEMENT IN CONTROLLED/ VERTICAL PLANT PRODUCTION: ARTIFICIAL INTELLIGENCE–BASED OPTIMIZATION STRATEGIES

ABSTRACT

Global population growth, urbanization, and climate change, along with pressures on traditional agriculture, have made innovative approaches such as closed and vertical crop production systems critical for food security and sustainability. While these systems offer high efficiency in land, water, and soil use, high energy consumption, particularly from artificial lighting and air conditioning, negatively impacts economic feasibility and environmental sustainability. This review article examines the role of AI-based strategies in optimizing light and energy management in CVBÜSs from a technical and analytical perspective. The article explores the transformative potential of AI, from spectral interactions on photosynthesis and plant morphology to the dynamic control of energy-efficient LED technologies and the intelligent management of HVAC systems. AI algorithms such as machine learning, deep learning, and reinforcement learning enable the development of adaptive and autonomous control strategies that maximize plant growth while minimizing energy consumption and operational costs. AI applications such as spectral optimization, dynamic light regimes, predictive climate control, and plant physiology predictions are improving the efficiency, crop quality, and sustainability of CVBUS. However, significant obstacles remain, including high initial costs, data management challenges, a lack of specialized personnel, and ethical concerns. It is emphasized that future research will overcome these challenges through renewable energy integration, more comprehensive data infrastructures, advanced algorithms, and modular system designs, thereby increasing the effectiveness and accessibility of AI-based CVBUS solutions. It is concluded that AI has the potential to revolutionize the future of agriculture by making CVBUS more efficient, economical, and sustainable.

Keywords: Indoor Crop Production, Vertical Farming, Artificial Intelligence, Light Management, Energy Optimization, Machine Learning, Reinforcement Learning, Sustainable Agriculture, Controlled Environment Agriculture, Smart Agriculture.

1. Giriş

Dünya nüfusunun hızla artması, kentleşme ve iklim değişikliğinin getirdiği çevresel zorluklar, geleneksel tarım yöntemlerinin sürdürülebilirliğini tehdit etmektedir. Bu bağlamda, kapalı ve dikey bitkisel üretim sistemleri gibi yenilikçi yaklaşımlar, gıda güvenliği ve sürdürülebilirlik açısından önemli bir potansiyel sunmaktadır. Bu sistemler, dar alanlarda yüksek verim sağlarken, su ve toprak kullanımını minimize ederek kaynak verimliliğini artırmaktadır (Ojo & Zahid, 2022). Ancak, kapalı ve dikey bitkisel üretim sistemlerinin yaygınlaşmasının önündeki en büyük engellerden biri, özellikle aydınlatma ve iklimlendirme sistemlerinden kaynaklanan yüksek enerji tüketimidir. Aydınlatma, bir dikey çiftlikteki enerji tüketiminin %65 ila %85'ini oluştururken, ısıtma, havalandırma ve iklimlendirme sistemleri %10 ila %20'sini oluşturur (Arcasi et al., 2023).

Bu yüksek enerji maliyetleri, kapalı ve dikey bitkisel üretim sistemlerinin ekonomik fizibilitesini ve çevresel sürdürülebilirliğini olumsuz etkilemektedir. Bu nedenle, bu sistemlerde ışık ve enerji yönetiminin optimize edilmesi, hem operasyonel maliyetleri düşürmek hem de çevresel ayak izini azaltmak için kritik öneme sahiptir (Aborujilah, 2025). Geleneksel yöntemlerle yapılan ışık ve enerji yönetimi, bitkinin farklı büyüme evrelerine ve çevresel koşullara dinamik olarak adapte olma yeteneğinden yoksundur. Bu durum, optimal olmayan büyüme koşullarına, enerji israfına ve düşük verimliliğe yol açabilmektedir (Kaiser et al., 2024).

Son yıllarda, yapay zekâ tabanlı teknolojiler, kapalı ve dikey bitkisel üretim sistemlerinde ışık ve enerji yönetimini optimize etme konusunda çığır açan fırsatlar sunmaktadır (Martin, 2024; Payili, 2025). Makine öğrenimi ve derin öğrenme algoritmaları, bitki büyüme verileri, çevresel sensör verileri ve enerji tüketim modellerini analiz ederek, bitki türüne ve gelişim evresine özel, dinamik ışık spektrumları ve yoğunlukları ile enerji verimli iklimlendirme stratejileri geliştirebilir. YZ tabanlı sistemler, enerji kullanımını optimize ederek, mevcut YZ dışı teknolojilere kıyasla enerji tüketiminde önemli azalmalar sağlayabilmektedir (Decardi-Nelson & You, 2024). Örneğin, yapay zeka tabanlı kontrol çerçeveleri, derin pekiştirmeli öğrenme tekniklerini kullanarak seralarda enerji verimli kontrol sağlayabilmektedir. Bu entegre yaklaşımlar, yalnızca kaynak kullanımını iyileştirmekle kalmaz, aynı zamanda mahsul verimini ve kalitesini artırarak sistemlerin genel sürdürülebilirliğini ve karlılığını yükseltir (Hoseinzadeh & Garcia, 2024).

Bu derleme makalesi, kapalı ve dikey bitkisel üretim sistemlerinde ışık ve enerji yönetiminin yapay zekâ tabanlı optimizasyon stratejilerini kapsamlı bir şekilde incelemeyi amaçlamaktadır. Makale, bu sistemlerin temel prensiplerini, ışık ve enerji yönetimindeki mevcut zorlukları, yapay zekânın bu zorlukları aşmada nasıl kullanılabileceğini ve gelecekteki potansiyel uygulamalarını teknik ve analitik bir yaklaşımla değerlendirecektir. Her paragrafta teknik bir açıklama, bilimsel veya fizyolojik bir mekanizmanın analizi, açık bir neden-sonuç ilişkisi ve gerektiğinde literatür tarzında kavramsal genişletmelerle konuyu derinlemesine ele alacaktır.

2. Kapalı/Dikey Bitkisel Üretim Sistemlerinin Temelleri

Kapalı ve dikey bitkisel üretim sistemleri, bitki yetiştiriciliğinde kontrollü bir ortam sağlayarak çevresel koşulları optimize etmeyi hedefleyen modern tarım yaklaşımlarıdır. Bu sistemler, topraksız tarım yöntemlerini (hidroponik, aeroponik, akuaponik gibi) dikey olarak istiflenmiş katmanlarda birleştirerek birim alandan elde edilen verimi maksimize eder (Malabadi et al., 2024; Sowmya et al., 2024). Temel prensip, ışık, sıcaklık, nem, karbondioksit konsantrasyonu ve besin çözeltisi gibi tüm büyüme faktörlerinin insan kontrolünde veya otomatik sistemler aracılığıyla hassas bir şekilde düzenlenmesidir (Stutte et al., 2023). Bu sayede, bitkiler dış iklim

koşullarından tamamen bağımsız olarak yıl boyunca optimum koşullarda yetiştirilebilir (Chatterjee et al., 2020, p. 6).

2.1. Tanım ve Kapsam

Kontrollü Çevre Tarımı, bitki büyümesini optimize etmek için çevresel koşulların yönetildiği tüm kapalı yapıları kapsayan geniş bir terimdir. Bu terim, gelişmiş seraları, büyüme odalarını ve özellikle yapay aydınlatmalı bitki fabrikalarını veya dikey çiftlikleri içerir (Dietze et al., 2024). Dikey tarım ise, ürünlerin dikey olarak istiflenmiş katmanlarda, kontrollü iç mekan koşullarında, genellikle yapay ışık ve topraksız yöntemler kullanılarak yetiştirildiği bir CEA türüdür. Bu yaklaşım, temel olarak güneş ışığı gibi doğal etkileşimleri dışarıda bırakarak yüksek düzeyde hassasiyet ve kontrol sunar (Stanghellini & Katzin, 2024).

2.2. Avantajlar

Kapalı ve dikey bitkisel üretim sistemleri, geleneksel tarıma kıyasla bir dizi önemli avantaj sunmaktadır:

Alan Verimliliği: Bitkilerin dikey katmanlarda yetiştirilmesi sayesinde, birim alandan elde edilen ürün miktarı önemli ölçüde artar. Bu durum, özellikle kentsel alanlarda sınırlı tarım arazisi sorununa çözüm sunar.

Kaynak Verimliliği: Topraksız yetiştirme yöntemleri ve kapalı sistemlerdeki su geri dönüşümü sayesinde, geleneksel tarıma kıyasla %70 ila %95'e kadar daha az su tüketilir. Benzer şekilde, besin maddeleri de daha verimli kullanılır (Malabadi et al., 2024).

Yıl Boyunca Üretim ve Yüksek Verim: Dış iklim koşullarından bağımsızlık, yıl boyunca tutarlı ve yüksek kalitede ürün elde edilmesini sağlar. Bitki türüne göre mevsimsel kısıtlamalar ortadan kalkar.

Pestisit ve Herbisit Kullanımının Azalması: Kapalı ve steril ortamlar, zararlı ve hastalıkların sisteme girişini sınırlar, böylece pestisit ve herbisit kullanımını büyük ölçüde azaltır veya tamamen ortadan kaldırır. Bu durum, daha sağlıklı ve güvenli gıda üretimine olanak tanır.

Kentsel Gıda Güvenliği ve Tedarik Zinciri Kısaltma: Üretim tesislerinin tüketime yakın kurulabilmesi, taşıma maliyetlerini ve karbon ayak izini azaltır. Ayrıca, taze ürünlerin daha hızlı bir şekilde tüketicilere ulaşmasını sağlar (Lubna et al., 2022).

İklim Değişikliğine Karşı Direnç: Aşırı hava olayları (kuraklık, sel, don vb.) ve mevsimsel değişikliklerden etkilenmeme, gıda üretiminde istikrar ve güvenilirlik sağlar.

2.3. Zorluklar

Avantajlarına rağmen, kapalı ve dikey bitkisel üretim sistemleri önemli zorluklarla karşı karşıyadır:

Yüksek Başlangıç ve İşletme Maliyetleri: Özellikle arazi alımı, tesis kurulumu, ileri teknoloji ekipmanları ve nitelikli işgücü gereksinimi yüksek başlangıç maliyetlerine yol açar.

Yüksek Enerji Tüketimi: Yapay aydınlatma ve iklimlendirme sistemleri, bu sistemlerin en büyük enerji tüketicileridir ve yüksek işletme maliyetlerine neden olur. Bu durum, geleneksel tarıma göre 100 kata kadar daha fazla enerji gerektirebilir (Gurung et al., 2024, p. 109).

Teknolojik Bağımlılık ve Bakım: Sistemler, sensörler, YZ ve robotik gibi sofistike teknolojilere bağımlıdır ve bu da karmaşık bakım ve işletme süreçlerini beraberinde getirir (Akintuyi, 2024, p. 120).

Uzman Personel İhtiyacı: Bu ileri teknoloji sistemlerin kurulumu, yönetimi ve optimizasyonu için ziraat, mühendislik ve yazılım alanlarında uzmanlaşmış personele ihtiyaç duyulmaktadır. Nitelikli personel eksikliği, yaygınlaşmanın önünde bir engel teşkil edebilir (Aborujilah, 2025).

Sınırlı Mahsul Çeşitliliği ve Ölçeklenebilirlik: Mevcut dikey çiftlikler genellikle yapraklı yeşillikler ve bazı meyveler gibi belirli ürünler üzerinde yoğunlaşmaktadır. Daha geniş bir mahsul yelpazesini ekonomik olarak üretmek ve büyük ölçekte üretim yapmak hala zorluk teşkil etmektedir (Delden et al., 2021).

Pazar Rekabeti: Sübvansiyonlarla desteklenen geleneksel tarım ürünleriyle rekabet etmek, dikey tarım ürünleri için bir ekonomik zorluk oluşturur (Gurung et al., 2024, p. 109).

2.4. Teknolojik Altyapı ve Gereksinimler

Kapalı ve dikey bitkisel üretim sistemlerinin başarılı bir şekilde çalışabilmesi için entegre bir teknolojik altyapıya ihtiyaç duyulmaktadır:

Yapay Aydınlatma Sistemleri: Özellikle LED'ler, bitki büyümesi için gerekli spektral kalitede ve yoğunlukta ışık sağlayarak fotosentezi optimize eder (Steward & Avery, 2022, p. 1).

İklim Kontrol Sistemleri: Sıcaklık, nem ve CO2 seviyelerini hassas bir şekilde düzenleyerek bitkiler için ideal bir mikroklima oluşturur.

Topraksız Yetiştirme Sistemleri: Hidroponik, aeroponik ve akuaponik gibi yöntemler, bitkilerin su ve besin maddelerini verimli bir şekilde almasını sağlar (kaur, 2021, p. 2).

Sensör Teknolojileri: Çevresel parametreleri (sıcaklık, nem, CO2, ışık yoğunluğu) ve bitki fizyolojik durumunu (pH, EC) sürekli olarak izler (Uyeh et al., 2022).

Otomasyon ve Kontrol Sistemleri: Sensör verilerine dayanarak aydınlatma, sulama, besin dağıtımı ve iklimlendirme sistemlerini otomatik olarak yönetir (Sezhian et al., 2024).

Veri Analizi ve Yapay Zekâ: Toplanan büyük veri setlerini analiz ederek büyüme modellerini tahmin eder, sistem performansını optimize eder ve karar alma süreçlerini destekler (Dietze et al., 2024; Ojo & Zahid, 2022).

Bu sistemlerin entegrasyonu ve verimli çalışması, yapay zekâ tabanlı optimizasyon stratejilerini vazgeçilmez kılmaktadır. Gelecek bölümde, ışık yönetiminin temel prensipleri ve optimal spektrum stratejileri detaylandırılacaktır.

3. Işık Yönetimi ve Optimal Spektrum Stratejileri

Bitkisel üretimde ışık, fotosentezin temel enerji kaynağı olmasının yanı sıra, bitkinin büyümesini, gelişimini ve morfolojisini doğrudan etkileyen kritik bir çevresel faktördür (Amirshekari & Fakhroleslam, 2025). Kapalı ve dikey bitkisel üretim sistemlerinde, doğal güneş ışığının sınırlı veya hiç olmaması nedeniyle, yapay aydınlatma sistemleri bitki gelişimi için vazgeçilmez bir unsurdur. Bu sistemlerde ışık yönetimi, sadece yeterli ışık miktarını sağlamakla kalmayıp, aynı zamanda ışığın kalitesini (spektral kompozisyon), yoğunluğunu ve fotoperiyodunu bitkinin ihtiyaçlarına göre optimize etmeyi gerektirir (Sena et al., 2024). Optimal ışık stratejileri, bitki verimini ve kalitesini artırırken, enerji tüketimini minimize etme potansiyeli sunar (Amirshekari & Fakhroleslam, 2025).

3.1. Fotosentezin Temelleri ve Işık Spektrumu İlişkisi

Fotosentez, bitkilerin ışık enerjisini kimyasal enerjiye dönüştürerek organik madde sentezlediği biyokimyasal bir süreçtir. Bu süreçte klorofil a ve klorofil b başta olmak üzere farklı pigmentler, ışığın belirli dalga boylarını absorbe eder. Fotosentetik aktivite, görünür ışık

spektrumunun (400-700 nm) belirli bölgelerinde yoğunlaşır; özellikle mavi (420-430 nm) ve kırmızı (620-670 nm) ışık, fotosentez için en etkili dalga boylarıdır (Wu et al., 2024). Kırmızı ışık, fotosentezin ana itici gücü olup, bitki biyokütlesi birikimi ve boy uzaması üzerinde önemli etkilere sahiptir (Тараканов et al., 2021). Mavi ışık ise, klorofil sentezini, stomaların açılmasını, gövde kısalmasını ve yaprak kalınlığını etkileyerek bitkinin morfolojik gelişiminde kilit rol oynar (Cavallaro & Muleo, 2022). Yeşil ışığın fotosentezdeki rolü daha önce düşük olarak kabul edilse de, son araştırmalar yeşil ışığın bitki kanopisinin derinliklerine nüfuz ederek fotosentetik verimliliğe katkıda bulunabildiğini ve fotoprotektif etkileri olduğunu göstermektedir (Trojak & Skowron, 2021). Amber ışık (590-620 nm) da fotosentetik verimlilik açısından önemli dalga boyları arasında yer almaktadır (Wu et al., 2024).

Bitkilerin ışığa verdikleri tepkiler, sadece klorofilin ışık absorbsiyonu ile sınırlı değildir; fitokromlar, kriptokromlar ve fototropinler gibi çeşitli fotoreseptörler, ışığın spektral kalitesindeki değişimleri algılayarak bitkinin fotomorfogenetik tepkilerini düzenler (Paradiso & Proietti, 2021). Bu fotoreseptörler, bitkinin çevresel koşullara adaptasyonunu sağlayarak tohum çimlenmesinden çiçeklenmeye kadar birçok gelişimsel süreci kontrol eder (Тараканов et al., 2021). Bu nedenle, ışık spektrumunun hassas bir şekilde ayarlanması, yalnızca fotosentetik verimi artırmakla kalmaz, aynı zamanda istenen bitki morfolojisi ve biyokimyasal bileşen profili elde etmek için de kullanılır (Stamford et al., 2023).

3.2. Optimal Spektrum Bileşimleri ve Bitki Tepkileri

Farklı bitki türleri ve hatta aynı bitkinin farklı gelişim evreleri, optimum büyüme ve metabolit üretimi için farklı ışık spektrumu bileşimlerine ihtiyaç duyar (Stamford et al., 2023). Bu durum, dinamik ve ayarlanabilir ışık kaynaklarının kapalı tarım sistemlerindeki önemini vurgular.

Mavi ve Kırmızı Işık Oranları: Genellikle bitki büyümesi ve biyokütle birikimi için kırmızı ışığın baskın olduğu, ancak mavi ışığın belirli bir oranda bulunmasının gerekli olduğu kabul edilir. Mavi ışık, stomatal iletkenliği artırarak CO2 alımını ve dolayısıyla fotosentezi teşvik edebilir. Aşırı mavi ışık ise bitki boyunu kısaltabilir ve yaprak alanını azaltabilirken, uygun oranlarda mavi-kırmızı kombinasyonları, yüksek fotosentetik performans ve bitki büyümesini teşvik etmektedir (Modarelli et al., 2022).

Yeşil Işığın Rolü: Yeşil ışık, bitki kanopisinin alt katmanlarına nüfuz etme yeteneği sayesinde, yüksek yoğunluklu aydınlatma altında alt yaprakların fotosentezine katkıda bulunur (Trojak & Skowron, 2021). Ayrıca, bitkilerin strese tepkilerini modüle ettiği ve bazı durumlarda büyüme stimülasyonuna yol açtığı gözlemlenmiştir (Тараканов et al., 2021).

Uzak Kırmızı ve Ultraviyole Işık: Uzak kırmızı ışık (700-800 nm), fitokrom sistemi aracılığıyla gövde uzamasını ve yaprak genişlemesini teşvik eder. Ultraviyole ışık (UV-A: 315-400 nm, UV-B: 280-315 nm), bitki metabolizmasında ikincil metabolitlerin üretimini (örneğin, antioksidanlar ve flavonoidler) tetikleyebilir, ancak yüksek yoğunluklarda bitkilere zarar verebilir (Stamford et al., 2023). Bu dalga boylarının dikkatli kullanımı, bitki kalitesini artırabilir.

Optimal spektrum bileşimleri, bitki türüne, büyüme aşamasına ve istenen ürün özelliklerine göre özelleştirilmelidir. Örneğin, marul gibi yapraklı sebzeler için belirli mavi-kırmızı oranları, antosiyanin gibi faydalı bileşenlerin üretimini artırabilirken, domates gibi meyveli bitkiler için farklı spektral stratejiler gerekebilir (Stamford et al., 2023). Bu karmaşık ilişkilerin yönetimi, yapay zekâ destekli sistemlerin devreye girdiği noktadır.

3.3. Enerji Verimli Aydınlatma Teknolojileri: LED Sistemler

Geleneksel aydınlatma kaynakları (örneğin, yüksek basınçlı sodyum lambalar), yüksek enerji tüketimi, ısı üretimi ve sınırlı spektrum ayarlanabilirliği nedeniyle kapalı bitkisel üretim sistemlerinde verimlilik sorunları yaratmaktadır. Bu bağlamda, Işık Yayan Diyot teknolojileri, sunduğu avantajlarla devrim niteliğinde bir çözüm sunmuştur (Cavallaro & Muleo, 2022; Sena et al., 2024).

Spektral Ayarlanabilirlik: LED'ler, farklı dalga boylarında (mavi, yeşil, kırmızı, uzak kırmızı vb.) hassas bir şekilde ışık üretebilme kapasitesine sahiptir. Bu özellik, bitkinin spesifik ihtiyaçlarına göre özelleştirilmiş ışık spektrumlarının oluşturulmasına olanak tanır. Büyümenin farklı aşamalarında veya belirli fizyolojik tepkileri tetiklemek için spektrumun dinamik olarak ayarlanabilmesi, bitki verimini ve kalitesini optimize eder (Lozano-Castellanos et al., 2025).

Yüksek Enerji Verimliliği: LED'ler, geleneksel lambalara kıyasla daha düşük enerji tüketimi ve daha yüksek lümen verimliliği sunar. Bu durum, özellikle dikey çiftliklerde aydınlatma kaynaklı yüksek enerji maliyetlerini önemli ölçüde düşürme potansiyeli taşır (Sena et al., 2024).

Düşük Isı Üretimi: LED'ler, ışık enerjisinin çoğunu bitkiye yönlendirirken, geleneksel lambalara göre çok daha az ısı üretir. Bu özellik, iklimlendirme yükünü azaltarak ek enerji tasarrufu sağlar ve bitki etrafındaki mikroklimanın daha hassas kontrolüne olanak tanır.

Uzun Ömür ve Küçük Boyut: LED'lerin uzun ömrü ve kompakt tasarımı, bakım maliyetlerini düşürür ve dikey tarım sistemlerinde alan kullanımını maksimize eder.

Dinamik Kontrol Yeteneği: LED sistemleri, ışık yoğunluğunun, spektrumun ve fotoperiyodun hassas bir şekilde kontrol edilmesine imkan tanır (Lozano-Castellanos et al., 2025). Bu dinamik kontrol, bitki büyümesini ve enerji tüketimini optimize etmek için kritik öneme sahiptir. Örneğin, dar spektrumlu ışık kullanımı, bitkisel materyalin kalitesini artırırken enerji tasarrufu sağlayabilir.

Bu teknolojik gelişmeler, bitkisel üretimde ışık yönetiminin pasif bir süreç olmaktan çıkıp, bitki fizyolojisine ve enerji verimliliğine duyarlı, aktif bir optimizasyon alanına dönüşmesine olanak sağlamıştır. Bir sonraki bölümde, yapay zekânın bu karmaşık ışık yönetimi stratejilerini nasıl daha ileriye taşıdığı incelenecektir.

4. Enerji Yönetimi ve İklimlendirme Stratejileri

Kapalı ve dikey bitkisel üretim sistemlerinde enerji maliyetleri, özellikle yapay aydınlatma ve iklimlendirme sistemlerinden kaynaklanan yüksek tüketim nedeniyle, işletme giderlerinin önemli bir kısmını oluşturmaktadır. Aydınlatma dışındaki iklim kontrol sistemleri, toplam enerji tüketiminin %10 ila %20'sini teşkil edebilir (Arcasi et al., 2023). Bitki büyümesi ve gelişimi için optimal çevresel koşulların sürdürülmesi hayati olmakla birlikte, bu koşulların sağlanması genellikle yoğun enerji girdisi gerektirir (Zhang et al., 2023). Bu nedenle, enerji yönetiminin etkin bir şekilde yapılması ve iklimlendirme stratejilerinin optimize edilmesi, KVBÜS'ün ekonomik sürdürülebilirliği ve çevresel ayak izinin azaltılması açısından kritik öneme sahiptir.

4.1. HVAC Sistemleri ve Enerji Verimliliği

Isıtma, Havalandırma ve İklimlendirme sistemleri, KVBÜS içinde sıcaklık, nem ve hava sirkülasyonunu kontrol eden temel bileşenlerdir. Bu sistemler, bitkilerin fotosentetik aktivitesini ve transpirasyon oranlarını doğrudan etkileyen mikroklimayı düzenler. Ancak,

geleneksel HVAC sistemlerinin yüksek enerji tüketimi, KVBÜS'ün karlılığını tehdit eden başlıca unsurlardan biridir (Zhang et al., 2023).

Enerji verimliliğini artırmak için modern KVBÜS'lerde çeşitli yaklaşımlar benimsenmektedir:

Akıllı HVAC Kontrolü: Sensörlerden gelen gerçek zamanlı verilerle entegre çalışan akıllı kontrol sistemleri, bitki türüne, büyüme evresine ve dış iklim koşullarına göre HVAC sistemlerinin çalışma parametrelerini dinamik olarak ayarlayabilir. Bu, gereksiz enerji harcamasını önler ve optimal koşulları daha verimli bir şekilde sürdürür (Mun et al., 2025). Örneğin, bir model, iklim kontrol stratejisini optimize ederek ve saatlik spesifik enerji tüketimini minimize ederek dış iklim koşullarının enerji tüketimi üzerindeki etkisini değerlendirmiştir. Bu tür gelişmiş kontrol, özellikle yaz aylarında çok düşük enerji tüketimine olanak tanıyabilir.

Enerji Geri Kazanım Sistemleri: KVBÜS'lerde hava değişimi sırasında kaybedilen ısı veya serinlik, enerji geri kazanım üniteleri (örneğin, ısı pompaları ve ısı geri kazanımlı vantilatörler) aracılığıyla geri dönüştürülebilir (Ng et al., 2023). Bu sistemler, dışarı atılan havadaki termal enerjiyi taze havaya aktararak ısıtma ve soğutma yüklerini azaltır. Özellikle soğuk ve ılıman iklimlerde, binaların enerji sistemleriyle entegre edilen dikey çiftlikler, ısıtma ve soğutma için önemli enerji tasarrufları sağlayabilir.

Yalıtım ve Yapı Malzemeleri: Yüksek yalıtım performansına sahip yapı malzemeleri ve tesis tasarımında termal köprülerin azaltılması, ısı transferini minimize ederek HVAC sistemlerinin yükünü düşürür (Şirin et al., 2024). Bu, özellikle soğuk iklimlerde enerji kayıplarını engellemek için kritik bir faktördür.

Pasif Soğutma ve Isıtma Teknikleri: Jeotermal enerji, gölgelendirme sistemleri, doğal havalandırma (uygun yerleşim ve tasarım ile) gibi pasif stratejiler, mekanik HVAC sistemlerine olan bağımlılığı azaltarak enerji tüketimini düşürebilir (Weidner et al., 2021, p. 114338).

4.2. Karbondioksit Yönetimi ve Nem Kontrolü

CO2 ve nem, KVBÜS içindeki bitki büyümesini ve enerji tüketimini etkileyen diğer önemli çevresel parametrelerdir.

CO2 Zenginleştirme: CO2, fotosentez için temel bir reaktanttır. KVBÜS'lerde CO2 konsantrasyonunun atmosferik seviyelerin (yaklaşık 400 ppm) üzerine çıkarılması (genellikle 800-1200 ppm'e kadar), bitkilerin fotosentetik verimliliğini ve büyüme oranlarını önemli ölçüde artırabilir. Ancak, CO2 zenginleştirme maliyetli bir süreç olabilir ve bu maliyeti optimize etmek için CO2'nin mekansal dağılımının ve bitki kanopisi içindeki emiliminin doğru bir şekilde yönetilmesi gerekir. Örneğin, ticari seralarda CO2 zenginleştirme verimliliği, artan fotosentezin enerji (CO2 eşdeğeri) miktarına oranı hesaplanarak analiz edilebilir (Zhang et al., 2023, p. 17277). Optimum CO2 konsantrasyonunun bitki türüne ve gelişim evresine göre belirlenmesi, hem verimliliği hem de maliyet etkinliğini artırır (Orsini et al., 2020, p. 300).

Nem Kontrolü: Bağıl nem, bitki transpirasyonunu, besin alımını ve hastalık gelişimini doğrudan etkiler. Optimal nem seviyeleri, bitkinin sağlıklı büyümesi için önemlidir. Yüksek nem, mantar hastalıklarına yol açabilirken, düşük nem transpirasyonu aşırı artırarak bitki stresine neden olabilir. Nem kontrolü genellikle yoğuşturma (havayı soğutarak) veya buharlaştırma (nem ekleyerek) yoluyla yapılır, her iki işlem de enerji gerektirir (Zhang et al., 2020). Termoelektrik klima sistemleri gibi yeni teknolojiler, geleneksel sistemlere kıyasla nem kontrolünde enerji maliyetlerini önemli ölçüde azaltma potansiyeli sunmaktadır.

Nem Geri Kazanımı: Bitki transpirasyonu sonucu açığa çıkan nem, dezenfekte edilerek bitkilerin sulanmasında yeniden kullanılabilir. Bu yaklaşım, su tasarrufu sağlarken, aynı

zamanda ortamdaki nem yükünü yöneterek iklimlendirme sistemlerinin dehumidifikasyon yükünü potansiyel olarak düşürebilir.

4.3. Entegre Kontrol ve Optimizasyon

KVBÜS'lerde enerji yönetimi ve iklimlendirme stratejilerinin başarısı, tüm çevresel faktörlerin (ışık, sıcaklık, nem, CO2) entegre bir şekilde yönetilmesine bağlıdır. Her bir faktör birbiriyle etkileşim halindedir; örneğin, yüksek ışık yoğunluğu sıcaklığı artırırken, CO2 zenginleştirme fotosentezi hızlandırabilir ve bitkinin suya olan ihtiyacını değiştirebilir. Bu karmaşık dinamikler, tekil faktörlere odaklanan yaklaşımların sınırlı kalmasına neden olur.

Bu nedenle, yapay zekâ tabanlı optimizasyon stratejileri, bu entegrasyonu sağlamak için vazgeçilmezdir. Sensör ağlarından gelen büyük veri setlerini (sıcaklık, nem, CO2, bitki büyüme hızı, enerji tüketimi vb.) analiz ederek, YZ algoritmaları, bitki büyümesini maksimize ederken enerji tüketimini minimize eden dinamik ve uyarlanabilir kontrol stratejileri geliştirebilir (Kaiser et al., 2024). Örneğin, YZ algoritmaları, elektrik fiyatlarındaki dalgalanmaları ve bitki fizyolojisindeki değişimleri dikkate alarak optimum üretim koşullarını ve ilgili maliyetleri sürekli olarak ayarlayabilir (Kaiser et al., 2024). Talep yanıt kontrolü gibi stratejiler, elektrik maliyetlerini %5 ila %30 oranında azaltabilir.

Sonuç olarak, KVBÜS'de enerji yönetimi ve iklimlendirme, sadece çevresel parametreleri kontrol etmekten öte, maliyet etkinliği ve sürdürülebilirlik hedeflerine ulaşmak için yenilikçi, entegre ve yapay zekâ destekli yaklaşımlar gerektiren karmaşık bir mühendislik alanıdır. Gelecek bölümde, yapay zekâ tabanlı optimizasyon stratejileri daha detaylı ele alınacaktır.

5. Yapay Zekâ Tabanlı Optimizasyon Stratejileri

Yapay zekâ ve özellikle makine öğrenimi ile derin öğrenme teknikleri, kapalı ve dikey bitkisel üretim sistemlerinde karşılaşılan karmaşık optimizasyon problemlerini çözmek için güçlü araçlar sunmaktadır. Bu sistemlerdeki çok sayıda çevresel değişken (ışık, sıcaklık, nem, CO2 konsantrasyonu vb.) ve bitki fizyolojisinin dinamik yapısı, geleneksel kontrol yöntemlerinin ötesine geçen adaptif ve akıllı yaklaşımları zorunlu kılmaktadır (Ojo & Zahid, 2022). YZ, bu değişkenler arasındaki karmaşık etkileşimleri analiz ederek bitki büyümesini, verimliliğini ve kalitesini maksimize ederken enerji ve kaynak tüketimini minimize etme potansiyeli taşır.

5.1. Işık Yönetiminde Yapay Zekâ Uygulamaları

Yapay aydınlatma, KVBÜS'deki en büyük enerji tüketicilerinden biri olduğundan, ışık parametrelerinin YZ ile optimize edilmesi büyük önem taşır (Lozano-Castellanos et al., 2025). YZ algoritmaları, bitki türüne, büyüme evresine ve istenen morfolojik veya biyokimyasal özelliklere göre ışık spektrumunu, yoğunluğunu ve fotoperiyodunu dinamik olarak ayarlayabilir:

Spektral Optimizasyon: ML modelleri, farklı ışık spektrumlarının bitki gelişimi, fotosentetik verimlilik ve metabolit üretimi üzerindeki etkilerini analiz ederek, belirli hedefler için (örneğin, biyokütle artışı, besin değeri, aroma profili) en uygun spektral bileşimleri belirleyebilir (Manoharan et al., 2024, p. 177). Sensörlerden (örneğin, spektral sensörler) toplanan verilerle beslenen bu modeller, bitkilerin anlık tepkilerine göre spektrumu gerçek zamanlı olarak modifiye edebilir.

Dinamik Işık Rejimleri: YZ, bitki büyüme modelleri, dış enerji fiyatları ve hatta bitkilerin fotosentetik kapasitesindeki günlük dalgalanmalar gibi faktörleri hesaba katarak ışık yoğunluğunu ve süresini (fotoperiyodu) optimize edebilir. Örneğin, bitkilerin ışık kesintilerine tolerans gösterme yeteneği kullanılarak, YZ tabanlı sistemler güncel enerji fiyatlarıyla uyumlu,

enerji maliyetlerini düşüren dinamik 24 saatlik aydınlatma programları tasarlayabilir (Abbaspour et al., 2025).

Enerji Verimli Aydınlatma Kontrolü: YZ destekli IoT sistemleri, LED aydınlatmanın spektral ayarlanabilirliğini kullanarak bitkinin ihtiyacından fazla veya az ışık vermeden en verimli şekilde aydınlatmayı sağlar (Kharraz et al., 2025). Bu sistemler, akıllı LED sistemleri aracılığıyla renk sıcaklığı ve ışık yoğunluğu üzerinde dinamik kontrol sağlayarak enerji kullanımını optimize eder (Manoharan et al., 2024, p. 177).

5.2. İklim Kontrolünde Yapay Zekâ Uygulamaları

İklim kontrolü, sıcaklık, nem, CO2 ve hava akışı gibi parametrelerin hassas yönetimini içerir. YZ, bu kompleks sistemi daha verimli ve adaptif hale getirir:

Tahmine Dayalı Kontrol: Derin öğrenme ve diğer ML teknikleri, sera ikliminin tarihsel verilerini, dış hava koşullarını ve bitki tepkilerini analiz ederek gelecekteki çevresel koşulları tahmin edebilir (Lee et al., 2024). Bu tahminler, HVAC sistemlerinin önleyici bir şekilde ayarlanmasına olanak tanır, böylece enerji tüketimi minimize edilirken bitki stresi önlenir (Ajagekar et al., 2022).

Optimal Kontrol Politikaları: Pekiştirmeli öğrenme algoritmaları, deneme-yanılma yoluyla çevresel koşulları öğrenir ve belirli bir ödül fonksiyonunu (örneğin, maksimum verim ve minimum enerji tüketimi) optimize eden kontrol politikaları geliştirir. Bu algoritmalar, zamanla adaptasyon yeteneği sayesinde değişen bitki büyüme evrelerine ve çevresel perturbasyonlara dinamik olarak yanıt verebilir (Ajagekar et al., 2022).

Sensör Füzyonu ve Veri Analizi: KVBÜS'lerdeki sensör ağlarından toplanan büyük hacimli veriler, YZ algoritmaları tarafından gerçek zamanlı olarak işlenir (Rathor et al., 2024). Bu veri füzyonu, bitki sağlığı, büyüme hızı ve çevresel koşullar hakkında kapsamlı bir anlayış sağlayarak, anormalliklerin tespiti ve hedefli müdahaleler için temel oluşturur.

5.3. Bitki Fizyolojisi ve Büyüme Tahmininde Yapay Zekâ

YZ, bitki fizyolojisinin ve büyüme dinamiklerinin daha derinlemesine anlaşılmasına ve tahmin edilmesine olanak tanır:

Büyüme Modeli Oluşturma: ML ve DL modelleri, çevresel veriler, genetik bilgiler ve görüntü işleme teknikleriyle toplanan bitki fenotipik verilerini kullanarak bitki büyüme modellerini oluşturabilir. Bu modeller, farklı çevresel rejimler altında bitki verimini, kalitesini ve gelişim hızını doğru bir şekilde tahmin edebilir (Hu & You, 2023).

Hastalık ve Stres Tespiti: YZ destekli bilgisayar görüşü ve görüntü işleme algoritmaları, bitkilerdeki hastalıkları, besin eksikliklerini veya stres belirtilerini erken aşamalarda tespit edebilir. Bu, hızlı müdahale ile verim kayıplarını önler ve pestisit/herbisit kullanımını azaltır (Rathor et al., 2024).

Verim ve Hasat Tahmini: YZ modelleri, bitki büyüme verilerini ve çevresel koşulları analiz ederek hasat zamanını ve beklenen verimi yüksek doğrulukla tahmin edebilir (Akintuyi, 2024, p. 118). Bu tahminler, tedarik zinciri yönetimini ve pazar stratejilerini optimize etmeye yardımcı olur.

5.4. Çok Amaçlı Optimizasyon ve Karar Destek Sistemleri

KVBÜS'lerdeki optimizasyon problemleri genellikle enerji tüketimini minimize etme, verimi maksimize etme ve ürün kalitesini artırma gibi birbiriyle çelişen birden çok hedefi içerir

(Arteaga-Cabrera et al., 2025). YZ, bu çok amaçlı optimizasyon problemlerini çözmek için etkili yöntemler sunar:

Evrimsel Algoritmalar: Genetik algoritmalar gibi evrimsel algoritmalar, doğal seçilim prensiplerinden ilham alarak potansiyel çözümlerden oluşan bir popülasyonu iteratif olarak geliştirir (Poyatos et al., 2025, p. 7). Bu algoritmalar, enerji optimizasyonunda sağlam ve esnek bir yaklaşım sağlayarak, karmaşık çözüm uzaylarında arama yapabilir ve Pareto optimal çözümler sunabilir.

Pekiştirmeli Öğrenme ve Derin Pekiştirmeli Öğrenme: RL, enerji optimizasyonu gibi dinamik karar verme problemlerinde uygulanabilir. DRL algoritmaları, özellikle çok amaçlı problemlerle başa çıkmada yüksek boyutlu durumlarda geleneksel EA'lardan daha iyi performans gösterebilir. RL, keşfetme (exploration) ve kullanma (exploitation) dengesini kurarak suboptimal öğrenme sonuçlarını engellemeyi hedefler (Hamdan et al., 2024, p. 722).

Hibrit Yaklaşımlar: İstatistiksel yöntemleri meta-sezgisel algoritmalarla birleştiren hibrit yaklaşımlar, hidroponik seralarda bitki üretim verimini maksimize ederken maliyetleri minimize etmeyi hedefleyen çok amaçlı problemleri çözmek için geliştirilmiştir (Sriprateep et al., 2024).

Dijital İkizler: Fiziksel sistemlerin sanal kopyaları olan dijital ikizler (digital twins), KVBÜS'ün iç mikroklimasını ve bitki durumlarını yüksek doğrulukla modellemek için YZ (özellikle fizik tabanlı derin öğrenme) tekniklerinden yararlanır (Lozano-Castellanos et al., 2025). Bu ikizler, kontrol değişkenlerini optimize etmek ve bitki büyümesini tahmin etmek için kullanılır, böylece kontrol ve karar verme süreçlerinde doğruluk artar (Hu & You, 2023).

Yapay zekâ tabanlı optimizasyon stratejileri, KVBÜS'ün sadece teknik verimliliğini değil, aynı zamanda ekonomik ve çevresel sürdürülebilirliğini de artırarak, gıda üretiminde yeni bir dönemin kapılarını aralamaktadır (Chowdhury et al., 2023; Sezhian et al., 2024). Gelecek bölümde, bu stratejilerin uygulanmasında karşılaşılan zorluklar ve gelecekteki araştırma yönelimleri ele alınacaktır.

6. Zorluklar, Gelecek Yönelimler

Kapalı ve dikey bitkisel üretim sistemlerinde yapay zekâ tabanlı ışık ve enerji optimizasyonu stratejileri, sürdürülebilir gıda üretimi için önemli potansiyeller sunsa da, bu teknolojilerin geniş çapta benimsenmesi ve tam potansiyeline ulaşması önünde bir dizi zorluk bulunmaktadır. Bu zorluklar, teknolojik, ekonomik, sosyal ve etik boyutlarda incelenebilir. Bununla birlikte, mevcut kısıtlamaların üstesinden gelmeye yönelik devam eden araştırmalar ve yenilikçi yaklaşımlar, gelecekte KVBÜS'ün gelişimini şekillendirecektir.

6.1. Mevcut Zorluklar

KVBÜS'lerde YZ tabanlı optimizasyonun etkinliğini sınırlayan temel engeller şunlardır:

Yüksek Başlangıç Maliyetleri ve Ekonomik Fizibilite: YZ destekli sistemlerin kurulumu, ileri teknoloji sensörler, otomasyon ekipmanları ve sofistike yazılım altyapısı gerektirdiğinden önemli sermaye yatırımları gerektirir. Bu yüksek peşin harcamalar, özellikle küçük ve orta ölçekli işletmeler için teknolojiye erişimde önemli bir engel teşkil etmektedir (Abbaspour et al., 2025, p. 1). Ayrıca, YZ sistemlerinin hesaplama maliyetlerini (donanım ve işletim) doğru bir şekilde tahmin etmek zor olabilir; bu durum, YZ'nin tarımdaki genel uygulanabilirliğine ilişkin kapsamlı maliyet analizlerinin eksikliğini ortaya koymaktadır.

Veri Yönetimi ve Analiz Zorlukları: KVBÜS'lerde büyük hacimli ve heterojen veri setleri (çevresel, bitkisel, enerji tüketimi) üretilmektedir. Bu verilerin toplanması, depolanması,

işlenmesi ve analiz edilmesi karmaşık veri yönetimi ve analiz yetenekleri gerektirir. Sensör yerleşimi, kalibrasyonu ve veri bütünlüğü sorunları, YZ modellerinin güvenilirliğini ve doğruluğunu etkileyebilir. Gerçek dünya verilerinin yetersizliği ve tutarsız raporlama standartları, YZ modellerinin geliştirilmesini ve doğrulanmasını zorlaştırmaktadır (Aborujilah, 2025).

Teknolojik Entegrasyon ve Uyumluluk: Farklı üreticilerin donanım ve yazılım bileşenlerinin (aydınlatma sistemleri, HVAC, sensörler) sorunsuz bir şekilde entegre edilmesi ve birlikte çalışabilmesi önemlidir. Özellikle çok katmanlı dikey hidroponik sistemlerin fiziksel yapısı, kablosuz sinyal girişimine neden olarak bağlantı ve iletişim sorunları yaratabilir (Azmi et al., 2024, p. 8). Bu entegrasyonun sağlanması, karmaşık mühendislik becerileri gerektirir ve uyumluluk sorunları operasyonel verimliliği düşürebilir.

Uzman Personel ve Dijital Okuryazarlık Eksikliği: YZ tabanlı sistemlerin tasarımı, uygulanması, yönetimi ve bakımı için tarım, mühendislik ve veri bilimi alanlarında yetkin personele ihtiyaç duyulmaktadır (Aborujilah, 2025). Nitelikli işgücüne erişimdeki sınırlamalar ve çiftçiler arasındaki dijital okuryazarlık farkı, bu teknolojilerin geniş çapta benimsenmesini engelleyebilir. Etkili uygulama için eğitim ve desteğin sağlanması kritik öneme sahiptir.

Bitki Biyolojisinin Karmaşıklığı ve Dinamik Modeller: Bitkilerin çevresel faktörlere verdiği tepkiler, türler arasında, gelişim evreleri arasında ve hatta aynı türün varyeteleri arasında önemli farklılıklar gösterir. Optimal ışık programlarının veya iklim kontrol stratejilerinin bitki türüne göre belirlenmesi kolay değildir. YZ modellerinin bu biyolojik karmaşıklığı tam olarak yakalayabilmesi ve dinamik koşullara adaptif olarak yanıt verebilmesi hala devam eden bir araştırma konusudur (Hu & You, 2023).

Siber Güvenlik ve Gizlilik Endişeleri: IoT cihazları ve YZ sistemleri, veri topladıkça ve paylaştıkça siber güvenlik risklerini ve veri gizliliği endişelerini beraberinde getirir (Azmi et al., 2024, p. 8). Çiftçi verilerinin sahipliği, kullanımı ve korunmasına ilişkin açık kurallar ve mekanizmalar oluşturulması gerekmektedir.

Etik ve Sosyal Meseleler: YZ'nin tarımda yaygınlaşması, işgücü piyasaları üzerinde (otomasyon nedeniyle işten çıkarmalar), çiftçilerin mahremiyeti üzerinde (gelişmiş izleme teknolojileri) ve teknolojiye erişimde eşitsizlikler yaratma potansiyeli gibi etik soruları gündeme getirmektedir. Geleneksel tarım ürünlerine kıyasla dikey çiftlik ürünlerinin "doğallığı"na ilişkin tüketici algıları da sosyal bir zorluk teşkil edebilir (Gurung et al., 2024, p. 109).

6.2. Gelecek Yönelimler

KVBÜS'lerde YZ tabanlı ışık ve enerji yönetiminin geleceği, mevcut zorlukların üstesinden gelmeye ve yeni araştırma alanlarını keşfetmeye odaklanacaktır:

Daha Kapsamlı ve Standartlaştırılmış Veri Altyapısı: YZ modellerinin etkinliğini artırmak için çok disiplinli, uzunlamasına saha çalışmaları ve standardize edilmiş metrik tanımlarına dayalı kapsamlı veri setlerinin oluşturulması gerekmektedir (Aborujilah, 2025). Bitki performans metriklerinin yanı sıra operasyonel maliyetleri içeren detaylı veri toplama, YZ teknolojilerinin fizibilitesinin daha bütünsel bir şekilde anlaşılmasını sağlayacaktır.

Yenilenebilir Enerji Entegrasyonu ve Hibrit Sistemler: Yüksek enerji tüketimi sorununu çözmek için KVBÜS'lerin yenilenebilir enerji kaynaklarıyla (güneş, rüzgar) stratejik entegrasyonu büyük önem taşımaktadır (Aborujilah, 2025). YZ, bu hibrit enerji sistemlerinin verimli yönetiminde ve elektrik şebekesiyle entegrasyonunda kritik bir rol oynayacaktır.

İleri Düzey YZ Modelleri ve Algoritmaları: Gelecekteki araştırmalar, özellikle pekiştirmeli öğrenme ve model tahmine dayalı kontrol gibi ileri düzey algoritmaların entegrasyonuna odaklanacaktır. Bu, belirsizliklere (örneğin, öngörülemeyen hava koşulları, sensör hataları) karşı daha sağlam ve uyarlanabilir kontrol stratejilerinin geliştirilmesini sağlayacaktır. YZ modellerinin farklı bitki türlerine genellenebilirliğini artırmak, tek bir mahsule özgü çözümler yerine daha genel RL kontrolörlerinin geliştirilmesiyle mümkün olacaktır (Laatum et al., 2024, p. 6).

Dijital İkizler ve Siber-Fiziksel-Biyolojik Sistemler: Fizik-bilgilendirilmiş derin öğrenme tekniklerinden yararlanılarak geliştirilen dijital ikizler, KVBÜS'ün iç mikroklimasını ve bitki durumlarını yüksek doğrulukla modelleyerek kontrol değişkenlerini optimize etmek ve bitki büyümesini tahmin etmek için kullanılmaya devam edecektir. Bu CPBS yaklaşımları, enerji yönetimi ve mahsul üretiminin entegre ve akıllı kontrolünü sağlayacaktır (Hu & You, 2023).

Etik ve Sosyal Çerçeveler: YZ'nin tarımda sorumlu ve sürdürülebilir bir şekilde uygulanmasını sağlamak için veri gizliliği, teknolojiye eşit erişim ve işgücü etkileri gibi etik sorunlara yönelik net yönergeler ve politikalar geliştirilmesi gerekmektedir.

Modülerlik ve Ölçeklenebilirlik: YZ tabanlı çözümlerin modüler ve ölçeklenebilir olması, farklı boyutlardaki ve yapılandırmalardaki KVBÜS'lere kolayca uygulanabilmesini sağlayacaktır.

7. Sonuç

Kapalı ve dikey bitkisel üretim sistemleri, küresel gıda güvenliği ve sürdürülebilirlik hedeflerine ulaşmada kilit bir rol oynamaktadır. Ancak, bu sistemlerin yaygınlaşmasının önündeki en büyük engellerden biri olan yüksek enerji tüketimi ve operasyonel maliyetler, YZ tabanlı optimizasyon stratejileri aracılığıyla aşılabilir. Bu derleme makalesi, ışık ve enerji yönetiminde YZ'nin sunduğu dönüştürücü potansiyeli; ışık spektrumunun fotosentez ve bitki morfolojisi üzerindeki etkilerinden, enerji verimli LED teknolojilerinin dinamik kontrolüne ve HVAC sistemlerinin akıllı yönetimine kadar teknik bir yaklaşımla ele almıştır.

Yapay zekâ algoritmaları, özellikle makine öğrenimi, derin öğrenme ve pekiştirmeli öğrenme teknikleri sayesinde, bitki büyümesini maksimize ederken enerji tüketimini ve operasyonel maliyetleri minimize eden adaptif ve özerk kontrol stratejileri geliştirilmesine olanak sağlamaktadır. Spektral optimizasyon, dinamik ışık rejimleri, tahmine dayalı iklim kontrolü ve bitki fizyolojisi tahminleri gibi YZ uygulamaları, KVBÜS'ün verimliliğini, mahsul kalitesini ve sürdürülebilirliğini artırmaktadır. Dijital ikizler ve çok amaçlı optimizasyon teknikleri ise, karmaşık sistem dinamiğini yöneterek en uygun çözüm setlerini sunmaktadır.

Bununla birlikte, YZ teknolojilerinin yaygın olarak benimsenmesinin önünde hala yüksek başlangıç maliyetleri, veri yönetimi zorlukları, uzman personel eksikliği ve etik kaygılar gibi önemli engeller bulunmaktadır. Gelecekteki araştırmalar, bu zorlukların üstesinden gelmeye, yenilenebilir enerji entegrasyonu, daha kapsamlı veri altyapıları, ileri düzey algoritmalar ve modüler sistem tasarımları aracılığıyla YZ tabanlı KVBÜS çözümlerinin etkinliğini ve erişilebilirliğini artırmaya odaklanacaktır. Yapay zekâ, kapalı ve dikey bitkisel üretim sistemlerini daha verimli, ekonomik ve sürdürülebilir hale getirerek, tarımın geleceğinde devrim yaratma potansiyelini taşımaktadır.

Yapay Zekâ Katkı Beyanı

Bu çalışmanın yazım sürecinde, yalnızca dil düzenleme, yazım kuralları, açıklık ve akıcılığın artırılması gibi amaçlarla yapay zekâ temelli yazılım programlarından yararlanılmıştır.

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TARIM KAYNAKLI PELET YAKITLARINDA YAŞAM DÖNGÜSÜ DEĞERLENDİRMESİ VE EMİSYON-ENERJİ OPTİMİZASYONU

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ÖZET

Küresel enerji talebinin artışı ve iklim değişikliğiyle mücadele hedefleri doğrultusunda, tarımsal kalıntılardan elde edilen pelet yakıtları, fosil yakıtlara sürdürülebilir bir alternatif olarak öne çıkmaktadır. Bu derleme makalesi, tarım kaynaklı pelet yakıtlarının yaşam döngüsü değerlendirmesi, emisyon-enerji optimizasyonu stratejileri, çevresel ve ekonomik etkileri ile gelecek perspektiflerini kapsamlı bir şekilde incelemektedir. Makale, bu yakıtların çevresel performansını ve sürdürülebilirlik potansiyelini nesnel bir şekilde değerlendirmek için Uluslararası Standardizasyon Örgütü'nün belirlediği 14040 ve 14044 standartlarına uygun LCA metodolojisinin önemini vurgulamaktadır.Analizler, tarımsal biyokütle hammaddelerinin (selüloz, hemiselüloz, lignin, kül içeriği) kimyasal ve fiziksel özelliklerinin pelet kalitesi ve yanma davranışı üzerindeki belirleyici etkilerini ortaya koymaktadır. Özellikle külün bileşimi ve miktarı, korozyon ve cüruf oluşumu gibi yanma problemlerini tetikleyebilmektedir. Pelet üretim sürecindeki kurutma ve yoğunlaştırma aşamalarının enerji yoğunluğu, atık ısı geri kazanımı ve ileri peletleme teknikleri (örneğin geç buhar enjeksiyonu) ile minimize edilebilirken, yanma sistemlerinde emisyon kontrolü için yanma odası tasarımı, hava beslemesi optimizasyonu ve ileri yanma kontrol sistemleri kritik öneme sahiptir. Ayrıca, biyokömür (torrefaction) gibi ön işlemler, hem yakıt kalitesini iyileştirmekte hem de emisyonları azaltmaktadır.Çevresel açıdan, tarım kaynaklı peletler genellikle karbon nötr bir yakıt olarak değerlendirilmekle birlikte, LCA çalışmaları, üretim ve taşıma aşamalarındaki fosil yakıt tüketiminin net sera gazı dengesi üzerindeki etkilerini göstermektedir. Makale, arazi kullanım değişiklikleri ve su kaynakları üzerindeki etkiler gibi diğer çevresel faktörlerin de bütünsel değerlendirilmesi gerektiğini belirtmektedir. Ekonomik perspektiften bakıldığında, tarımsal peletler yüksek pazar potansiyeline sahiptir ve kırsal ekonomilere katkıda bulunurken istihdam yaratma kapasitesine sahiptir. Ancak, rekabetçilik, üretim maliyetleri ve hükümet politikalarına bağlıdır.Gelecek perspektifleri, ileri proses teknolojileri, döngüsel biyoekonomi entegrasyonu, geliştirilmiş politika ve pazar mekanizmaları ile sürekli teknolojik gelişmeleri içermektedir. Bu alanlardaki sürekli araştırma ve geliştirme, tarım kaynaklı pelet yakıtlarının sürdürülebilir enerji dönüşümündeki rolünü pekiştirecek, çevresel faydalarını maksimize ederken ekonomik uygulanabilirliğini ve toplumsal kabulünü artıracaktır.

Anahtar Kelimeler Tarımsal pelet yakıtları, Yaşam döngüsü değerlendirmesi (LCA), Emisyon ve enerji optimizasyonu, Pelet kalitesi ve yanma davranışı, Sürdürülebilir biyoenerji.

LIFE CYCLE ASSESSMENT AND EMISSION–ENERGY OPTIMIZATION IN AGRICULTURAL BIOMASS PELLET FUELS

ABSTRACT

In line with the increasing global energy demand and the goals of combating climate change, pellet fuels derived from agricultural residues are emerging as a sustainable alternative to fossil fuels. This review article comprehensively examines the life cycle assessment, emission-energy optimization strategies, environmental and economic impacts, and future perspectives of agricultural pellet fuels. The article emphasizes the importance of the LCA methodology, compliant with the International Organization for Standardization (IOS) standards 14040 and 14044, to objectively assess the environmental performance and sustainability potential of these fuels. The analyses reveal the decisive effects of the chemical and physical properties of agricultural biomass feedstocks (cellulose, hemicellulose, lignin, ash content) on pellet quality and combustion behavior. In particular, the composition and amount of ash can trigger combustion problems such as corrosion and slag formation. The energy intensity of the drying and densification stages of the pellet production process can be minimized through waste heat recovery and advanced pelletization techniques (e.g., late steam injection). Combustion chamber design, air supply optimization, and advanced combustion control systems are critical for emission control in combustion systems. Furthermore, pretreatments such as biochar (torrefaction) both improve fuel quality and reduce emissions. From an environmental perspective, while agricultural pellets are generally considered a carbon-neutral fuel, LCA studies demonstrate the impact of fossil fuel consumption during production and transportation on the net greenhouse gas balance. The article suggests that other environmental factors, such as land use changes and impacts on water resources, should also be considered holistically. From an economic perspective, agricultural pellets have high market potential and can contribute to rural economies and create employment. However, competitiveness depends on production costs and government policies. Future perspectives include advanced process technologies, integration with the circular bioeconomy, improved policy and market mechanisms, and continued technological advancements. Continued research and development in these areas will reinforce the role of agricultural pellet fuels in the sustainable energy transition, increasing their economic viability and societal acceptance while maximizing their environmental benefits.

Keywords: Agricultural pellet fuels, Life Cycle Assessment (LCA), Emission and energy optimization, Pellet quality and combustion behavior, Sustainable bioenergy.

1. Giriş

Küresel enerji sistemlerinde fosil yakıtlara olan bağımlılığın azaltılması yönündeki acil ihtiyaç, yenilenebilir enerji kaynaklarına geçişi hızlandırmış ve bu dönüşümde biyokütlenin stratejik rolünü ön plana çıkarmıştır (Nosenzo & Kelman, 2025, p. 1). Biyokütle, özellikle tarımsal kalıntılardan elde edilen pelet yakıtları formunda, karbon nötr bir enerji kaynağı olarak değerlendirilmekte ve küresel dekarbonizasyon hedeflerine ulaşmada önemli bir potansiyel taşımaktadır. Bu yakıtların kullanımı, sadece enerji güvenliğini artırmakla kalmayıp, aynı zamanda tarım sektöründeki atıkların değerlendirilmesi ve döngüsel biyoekonomik modellerin desteklenmesi açısından da kritik bir fonksiyon icra etmektedir (Ibrahim et al., 2025; Svensson et al., 2024). Ancak, biyokütle peletlerinin enerji dönüşüm sistemlerindeki yaygınlaşması, hammaddenin karakteristik özelliklerinden nihai ürünün kalitesine, lojistik süreçlerden çevresel etkilerine kadar uzanan bir dizi teknik ve çevresel optimizasyonu zorunlu kılmaktadır.

Tarımsal atıkların peletlenerek enerjiye dönüştürülmesi, atık yönetimi sorunlarına sürdürülebilir bir çözüm sunarken, aynı zamanda hava kalitesi üzerindeki olumsuz etkileri azaltma potansiyeli taşımaktadır (Nosenzo & Kelman, 2025, p. 3). Geleneksel olarak yakılarak veya depolanarak bertaraf edilen büyük miktardaki tarımsal kalıntılar, pelet formunda sıkıştırıldığında hem nakliye ve depolama maliyetlerini düşürür hem de daha verimli ve temiz bir yanma profili sunar (Ibrahim et al., 2025). Özellikle mısır sapı ve pirinç kabuğu gibi lignoselülozik biyokütle kaynakları, yüksek ısıtma değerleri sayesinde kömüre eşdeğer enerji içeriği sağlayarak yenilenebilir enerji üretimi için cazip bir alternatif oluşturmaktadır (Mujtaba et al., 2023). Bu dönüşüm süreci, hammaddenin başlangıçtaki düşük yoğunluk ve yüksek nem içeriği gibi dezavantajlarını gidermekle birlikte (Găgeanu et al., 2021), nihai peletin fiziksel, mekanik, kimyasal ve termal özelliklerinin optimize edilmesi yoluyla yakıt kalitesini maksimize etmeyi hedefler.

Bu derleme makalesi, tarım kaynaklı pelet yakıtlarının yaşam döngüsü değerlendirmesi ve emisyon-enerji optimizasyonu üzerine odaklanacaktır. LCA, biyoyakıt üretiminin çevresel yüklerini, hammadde temininden nihai enerji kullanımına kadar tüm yaşam döngüsü boyunca kapsamlı bir şekilde değerlendiren bilimsel bir metodolojidir (Osman et al., 2024). Bu yaklaşım, pelet üretimi ve kullanımından kaynaklanan sera gazı emisyonları, enerji tüketimi ve diğer çevresel etkilerin nicel analizini sağlayarak, sürdürülebilirlik potansiyelinin objektif bir şekilde belirlenmesine olanak tanır (Martín-Gamboa et al., 2020). Ayrıca, makale, pelet üretim süreçlerinde ve yanma sistemlerinde emisyonları minimize etmeye ve enerji verimliliğini maksimize etmeye yönelik teknik yaklaşımları ve optimizasyon stratejilerini de detaylı bir şekilde inceleyecektir. Bu analiz, tarım kaynaklı pelet yakıtlarının çevresel performansını artırma ve enerji sektöründeki sürdürülebilir entegrasyonlarını destekleme amacıyla kritik mühendislik ve bilimsel perspektifler sunmayı hedeflemektedir.

2. Yaşam Döngüsü Değerlendirmesi Metodolojileri ve Uygulamaları

Tarımsal kaynaklı pelet yakıtlarının çevresel performansını ve sürdürülebilirlik potansiyelini nesnel bir şekilde değerlendirmek için Yaşam Döngüsü Değerlendirmesi metodolojisi kritik bir araçtır (Prasad et al., 2020). LCA, bir ürünün veya hizmetin, hammaddelerin temininden nihai bertarafına kadar uzanan tüm yaşam döngüsü boyunca çevresel etkilerini sistematik olarak nicelendirir. Bu bütünsel yaklaşım, sadece doğrudan emisyonları değil, aynı zamanda üretim, taşıma, işleme ve kullanım aşamalarındaki enerji tüketimi ve kaynak kullanımı gibi dolaylı etkileri de dikkate alarak, gizli çevresel yüklerin ortaya çıkarılmasını sağlar (Sgarbossa et al., 2020). Böylece, tarım kaynaklı peletlerin geleneksel fosil yakıtlara göre gerçek çevresel avantajlarını veya potansiyel dezavantajlarını belirlemek mümkün hale gelirken, aynı zamanda süreç iyileştirmeleri için de yol gösterici veriler sunulur (Osman et al., 2021, p. 4092).

2.1. LCA'nın Temel Prensipleri ve ISO Standartları

Yaşam Döngüsü Değerlendirmesi, Uluslararası Standardizasyon Örgütü tarafından geliştirilen ISO 14040 ve ISO 14044 standartları ile uluslararası düzeyde kabul görmüş bir metodolojik çerçeveye sahiptir (Khan, 2022, p. 61). Bu standartlar, LCA çalışmalarının şeffaflığını, karşılaştırılabilirliğini ve tekrarlanabilirliğini sağlamak amacıyla temel prensipleri ve aşamaları belirler. Ancak, aynı ürün sistemleri üzerinde yapılan LCA çalışmalarında bile geniş bir sonuç çeşitliliğinin gözlemlenmesi, metodolojik tercihlerin ve uygulama farklılıklarının önemini vurgular. Bu farklılıklar, özellikle biyoyakıtların LCA'sında, kullanılan modellerin ve veri tabanlarının çeşitliliği ile birlikte, standardizasyonun detaylı uygulama kılavuzlarına olan ihtiyacını ortaya koymaktadır. LCA'nın nihai amacı, çevresel sürdürülebilirliği artırmak ve politika yapıcılar için uzun vadeli stratejik kararların alınmasında kanıta dayalı veriler sunmaktır (Osman et al., 2021, p. 4092).

2.2. Yaşam Döngüsü Değerlendirme Aşamaları

ISO 14040 ve 14044 standartlarına göre, bir LCA çalışması dört ana aşamadan oluşur:

Hedef ve Kapsam Tanımı: Bu aşama, çalışmanın amacını, hedeflerini ve sınırlarını belirler. Fonksiyonel birim, yani değerlendirilen ürün veya hizmetin nicel ölçüsü ve sistem sınırları, bu adımda tanımlanır (Rashedi et al., 2022, p. 6). Örneğin, tarım kaynaklı pelet yakıtları için fonksiyonel birim, bir kilogram peletin veya belirli bir enerji miktarının (örneğin 1 MJ enerji) üretimi olabilir. Sistem sınırları ise, hammadde temininden pelet üretimine, taşımasına ve nihai kullanımına kadar tüm süreçleri kapsar (Miller & Orton, 2021, p. 4). Bu tanımlar, sonuçların güvenilirliği ve karşılaştırılabilirliği için hayati öneme sahiptir.

Yaşam Döngüsü Envanter Analizi: Bu aşamada, tanımlanan sistem sınırları içinde tüm girdi ve çıktı akışları (hammadde, enerji, su, hava emisyonları, atıklar vb.) toplanır ve nicelendirilir. Tarım kaynaklı pelet üretiminde, tarımsal kalıntıların toplanması, kurutulması, öğütülmesi, peletlenmesi ve taşınması gibi her bir aşamadaki enerji ve malzeme tüketimleri, sera gazı emisyonları ve diğer çevresel çıktılar detaylı olarak kaydedilir (Sadaghiani et al., 2023). LCI verileri, bir sonraki etki değerlendirme aşamasının temelini oluşturur.

Yaşam Döngüsü Etki Değerlendirmesi: Bu aşamada, LCI'den elde edilen girdi ve çıktı verileri, çeşitli çevresel etki kategorileri (örneğin, küresel ısınma potansiyeli, asitlenme, ötrofikasyon, fosil yakıt tükenmesi, insan sağlığı üzerindeki etkiler) altında çevresel etkilere dönüştürülür (Sadaghiani et al., 2023). Her bir emisyon veya kaynak kullanımı, ilgili etki kategorisi için bir karakterizasyon faktörü ile çarpılarak potansiyel çevresel etki hesaplanır. Örneğin, karbondioksit emisyonları, küresel ısınma potansiyeli kategorisi altında birim olarak CO2 eşdeğeri (CO2e) cinsinden ifade edilir.

Yaşam Döngüsü Yorumlaması: Son aşama, envanter analizi ve etki değerlendirme sonuçlarının derlenip, tanımlanan hedef ve kapsama göre yorumlanmasını içerir (Osman et al., 2021, p. 4092). Bu aşamada, çevresel açıdan en kritik noktalar (hotspotlar) belirlenir, hassasiyet analizleri yapılır ve sonuçların belirsizlikleri değerlendirilir. Elde edilen bulgular, ürünün çevresel performansını iyileştirmek için öneriler sunmak, farklı alternatifler arasında karşılaştırma yapmak ve politika kararlarını bilgilendirmek amacıyla kullanılır.

2.3. Tarım Kaynaklı Pelet Yakıtlarında LCA Uygulamalarına Özgü Hususlar

Tarım kaynaklı pelet yakıtlarının LCA'sında, biyokütlenin doğasından kaynaklanan bazı özel hususlar bulunmaktadır. Özellikle, biyoenerji sistemlerinin karbon ayak izinin belirlenmesinde, biyojenik karbonun modellenmesi büyük önem taşır (Martín-Gamboa et al., 2020). Biyokütle büyümesi sırasında atmosferden alınan CO2 ile yanma sonucu atmosfere salınan CO2

arasındaki denge, karbon nötrlüğü argümanının temelini oluşturur. Ancak, arazi kullanım değişiklikleri veya dolaylı arazi kullanım değişiklikleri (iLUC) gibi faktörler, LCA sonuçlarını önemli ölçüde etkileyebilir. Ayrıca, tarımsal atıkların "atık" olarak kabul edilmesi ve bunların alternatif kullanım senaryoları (örneğin toprakta bırakılması) ile kıyaslanması, LCA'nın sistem sınırları ve çok fonksiyonluluk (multifunctionality) ile ilgili tahsisat (allocation) yöntemlerinin dikkatli bir şekilde seçilmesini gerektirir. Bu metodolojik seçimler, LCA sonuçlarının güvenilirliğini ve uygulanabilirliğini doğrudan etkiler, bu nedenle literatürdeki geniş varyasyonun ana nedenlerinden biridir (Martín-Gamboa et al., 2020).

3. Tarımsal Biyokütle Hammaddeleri ve Peletleme Süreci

Tarımsal kaynaklı pelet yakıtlarının çevresel performansının yaşam döngüsü değerlendirmesi ve emisyon-enerji optimizasyonu, büyük ölçüde kullanılan biyokütle hammaddelerinin karakteristik özelliklerine ve uygulanan peletleme süreçlerine bağlıdır. Hammaddelerin kimyasal ve fiziksel özellikleri, peletlerin nihai yakıt kalitesini, depolama davranışını ve yanma özelliklerini doğrudan etkilerken, peletleme süreci parametreleri ise üretim verimliliği ve ürün dayanıklılığı açısından kritik rol oynar (Lavergne et al., 2021).

3.1. Tarımsal Biyokütle Hammaddelerinin Özellikleri

Tarımsal kalıntılar, lignoselülozik yapıya sahip olup, temel olarak selüloz, hemiselüloz ve lignin içerirler (Mujtaba et al., 2023). Bu bileşenlerin oranları, biyokütlenin türüne ve menşeine göre değişiklik gösterir ve peletlerin mekanik dayanımı ile enerji içeriği üzerinde belirleyici etkilere sahiptir. Örneğin, yüksek lignin içeriği, peletleme sırasında doğal bir bağlayıcı görevi görerek peletlerin dayanıklılığını artırabilir.

Kimyasal Bileşim:

Selüloz ve Hemiselüloz: Biyokütlenin ana yapısal bileşenleridir ve yüksek kalorifik değere katkıda bulunurlar. Termal bozunma sıcaklıkları genellikle lignine göre daha düşüktür; hemiselüloz yaklaşık 200-220 °C'den itibaren, selüloz ise yaklaşık 270-315 °C'den itibaren bozunmaya başlarken, lignin daha geniş bir sıcaklık aralığında, daha yüksek sıcaklıklara kadar bozunur (El-Sayed et al., 2023, p. 17779).

Lignin: Biyokütleye rijitlik ve su geçirmezlik sağlayan amorf bir polimerdir. Peletleme esnasında yüksek sıcaklık ve basınç altında yumuşayarak partiküller arası bağ oluşumunu destekler.

Kül İçeriği: Tarımsal kalıntıların önemli bir özelliği olan yüksek kül içeriği, pelet yakıtlarının yanma verimliliğini düşürebilir ve külün erime noktasına bağlı olarak cüruf oluşumuna neden olabilir (Peng & Lau, 2019, p. 226). Külün bileşimi, özellikle alkali metaller (potasyum, sodyum) ve klor gibi elementlerin varlığı, kül erime davranışını, depozit oluşumunu ve yanma sistemlerinde yüksek sıcaklık korozyon potansiyelini önemli ölçüde artırır (Karczewski et al., 2016, p. 113).

Uçucu Madde ve Sabit Karbon: Bu oranlar, yakıtın yanma davranışını ve tutuşma karakteristiğini belirler. Yüksek uçucu madde içeriği hızlı tutuşmaya yol açarken, sabit karbon yakıtın ısıtma değerine önemli katkıda bulunur (FİGEN et al., 2016, p. 3).

Fiziksel Özellikler:

Nem İçeriği: Peletleme süreci için kritik bir parametredir. Optimal nem içeriği aralığı, biyokütle türüne göre değişmekle birlikte, genellikle %10-20 civarındadır (Jiang et al., 2019, p. 558). Aşırı nem, pelet dayanıklılığını düşürürken, çok düşük nem de bağlayıcıların

aktivasyonunu zorlaştırabilir ve üretim için daha fazla enerji gerektirebilir (Găgeanu et al., 2021).

Partikül Boyutu: Peletleme öncesinde hammaddenin öğütülerek homojen bir partikül boyutuna getirilmesi, pelet kalitesi ve yoğunluğu için hayati öneme sahiptir. Daha küçük partikül boyutları, daha fazla temas yüzeyi sağlayarak partiküller arası bağ oluşumunu kolaylaştırır ve daha dayanıklı peletler elde edilmesini sağlar (Labbé et al., 2019). Ancak çok ince partiküllerin aşırı üretimi, eleme sırasında toz oluşumuna yol açabilir ve bu tozlar, depolama ve taşıma süreçlerinde sağlık, güvenlik riskleri (toz patlamaları) ile yanma sistemlerinde sorunlara neden olabilir.

Yığın Yoğunluğu: Hammaddenin düşük yığın yoğunluğu, depolama ve taşıma maliyetlerini artıran temel bir dezavantajdır. Peletleme işlemi, bu yığın yoğunluğunu önemli ölçüde artırarak bu lojistik sorunları giderir (Rashedi et al., 2022, p. 2).

3.2. Peletleme Süreci Aşamaları

Peletleme süreci, tarımsal biyokütleyi yüksek yoğunluklu, homojen ve standartlaştırılmış yakıtlara dönüştüren bir dizi adımdan oluşur (Ibitoye et al., 2021). Bu süreç genellikle ön işlemler, yoğunlaştırma ve son işlemler olarak üç ana aşamada incelenebilir:

Ön İşlemler:

Kurutma: Yüksek nem içeriği, pelet üretimini olumsuz etkilediği için biyokütle genellikle optimal nem seviyesine kadar kurutulur. Kurutma, pelet kalitesini artırırken, aynı zamanda enerji yoğun bir süreçtir ve LCA'da önemli bir çevresel yüke neden olabilir (Jacob-Lopes & Zepka, 2017, p. 485).

Boyut Küçültme: Hammadde, homojen bir partikül boyutu dağılımı elde etmek için öğütülür veya parçalanır. Bu adım, peletleme verimliliğini ve nihai ürün kalitesini doğrudan etkiler (Zăbavă et al., 2018, p. 4).

Karıştırma ve Kondisyonlama: Farklı biyokütle türleri karıştırılabilir ve bazen bağlayıcı maddeler (örneğin nişasta, melas) veya su buharı ile kondisyonlama yapılabilir. Bu, peletleme sürecini kolaylaştırır ve peletlerin mekanik dayanımını artırır (Nath et al., 2023, p. 2).

Yoğunlaştırma:

Bu aşamada, ön işlemden geçmiş biyokütle, pelet değirmenleri (halka kalıp veya düz kalıp tipi) veya ekstrüzyon presleri gibi ekipmanlar kullanılarak yüksek basınç ve sıcaklık altında sıkıştırılır (Tumuluru et al., 2010, p. 2). Sıkıştırma sırasında oluşan sürtünme ve basınç, biyokütlenin doğal bağlayıcıları olan lignin ve hemiselülozun yumuşamasını sağlar. Bu durum, partiküllerin birbirine yapışmasını ve pelet formunu korumasını sağlar (Rashedi et al., 2022, p. 2).

İşlem sırasında sıcaklık genellikle 90-100°C'ye ulaşabilir, bu da biyokütlenin yapısal bütünlüğünü güçlendirir (Jacob-Lopes & Zepka, 2017, p. 485).

Son İşlemler:

Soğutma: Peletler, yoğunlaştırma sonrası yüksek sıcaklıkta oldukları için soğutulmalıdır. Soğutma işlemi, peletlerin sertleşmesini ve şekillerini korumasını sağlar.

Eleme: Soğutma sonrası oluşan ince partiküller (toz) elenerek çıkarılır. Bu, peletlerin kalitesini ve depolama/taşıma güvenliğini artırır.

3.3. Pelet Kalitesini Etkileyen Faktörler ve Optimizasyon

Pelet kalitesi, nihai kullanım performansını ve ekonomik değeri belirleyen çeşitli parametrelerle tanımlanır. Bu parametrelerin optimizasyonu, üretim maliyetlerini düşürme ve çevresel etkiyi azaltma açısından önemlidir.

Hammaddenin Özellikleri: Biyokütlenin nem içeriği, partikül boyutu ve kimyasal bileşimi (kül, lignin içeriği) pelet dayanıklılığı, yoğunluğu ve ısıtma değeri üzerinde doğrudan etkilidir (Lavergne et al., 2021). Örneğin, optimal nem içeriği, peletin mekanik dayanımını ve yığın yoğunluğunu artırırken (Lavergne et al., 2021), daha küçük partikül boyutları daha yüksek yoğunluk ve dayanıklılık sağlayabilir.

İşlem Parametreleri: Peletleme sıcaklığı ve basıncı, pelet oluşum mekanizmasını etkileyen temel faktörlerdir. Yüksek sıcaklıklar ve basınçlar, lignin akışını artırarak daha güçlü bağlar ve dolayısıyla daha dayanıklı peletler oluşturabilir. Pelet değirmeninin die çapı ve sıkıştırma oranı da peletlerin yoğunluğunu ve dayanıklılığını etkiler (Ibitoye et al., 2021, p. 80).

Bağlayıcı Kullanımı: Bazı biyokütle türleri, özellikle düşük lignin içeriğine sahip olanlar, pelet dayanıklılığını artırmak için harici bağlayıcılara (örneğin melas, nişasta) ihtiyaç duyabilir (Nath et al., 2023, p. 2). Bu bağlayıcıların türü ve miktarı, nihai pelet kalitesini ve üretim maliyetini etkiler.

4. Emisyon ve Enerji Optimizasyonu Stratejileri

Tarımsal pelet yakıtlarının çevresel performansını ve ekonomik uygulanabilirliğini artırmak, hem üretim aşamalarında enerji tüketiminin azaltılmasını hem de yanma süreçlerinde emisyonların kontrol altına alınmasını gerektirir. Bu iki anahtar alan, pelet yakıtlarının sürdürülebilir enerji sistemlerine entegrasyonu için kritik optimizasyon stratejileri sunmaktadır.

4.1. Pelet Üretiminde Enerji Optimizasyonu

Pelet üretimi, özellikle kurutma ve yoğunlaştırma (peletleme) aşamaları nedeniyle enerji yoğun bir süreçtir. Bu süreçlerin optimizasyonu, hem operasyonel maliyetleri düşürmek hem de üretimden kaynaklanan çevresel ayak izini azaltmak için elzemdir (Asif et al., 2024).

Kurutma Süreçlerinin Verimliliği: Biyokütlenin peletleme öncesinde optimal nem içeriğine getirilmesi gerekliliği, kurutma operasyonunu enerji tüketiminde önemli bir paya sahip kılar. Bu nedenle, kurutma proseslerinin enerji ve ekserji analizi yoluyla optimizasyonu büyük önem taşır (Silva et al., 2021). Atık ısı geri kazanımı ve entegre kurutma sistemleri, bu aşamanın enerji verimliliğini artırmak için etkili yöntemlerdir. Örneğin, baca gazlarından veya diğer proseslerden elde edilen düşük dereceli atık ısının, biyokütlenin ön kurutması için kullanılması, enerji girdilerini ve dolayısıyla üretim maliyetlerini önemli ölçüde azaltabilir (Rudolfsson et al., 2020).

İleri Peletleme Teknikleri: Peletleme süreci sırasında enerji tüketimini azaltmaya yönelik yenilikçi teknikler geliştirilmektedir. "Geç buhar enjeksiyonu" (late-steam injection) gibi yöntemler, peletleme sırasında buhar tüketimini ve hammaddenin kurutma ihtiyacını önemli ölçüde azaltarak enerji tasarrufu ve daha iyi çevresel performans sağlamaktadır. Bu tür teknikler, pelet üretiminde kullanılan enerjinin ekonomik ve çevresel profilini iyileştirir (Rudolfsson et al., 2020).

Ön İşlem Optimizasyonu: Peletleme adımı tek başına değil, tüm ön işlem zinciri, yani taşıma, ön işleme ve depolama aşamaları enerji tüketimi ve maliyetler açısından kritik rol oynar. Malzeme kaybını minimize ederken işlenebilirliği ve yakıt verimini artırmak için partikül

boyutunun dengelenmesi gibi stratejiler, hem teknik hem de ekonomik verimlilik için önemlidir (Thompson et al., 2024). Ayrıca, geleneksel peletleme süreçleri, yüksek nemli peletleme süreçleri ve amonyak fiber genişlemesi gibi farklı peletleme teknolojilerinin karşılaştırmalı analizi, en verimli ve ekonomik yöntemin seçilmesinde yol göstericidir (Tazzit et al., 2021).

Süreç Parametrelerinin Kontrolü: Peletleme hızı, maksimum kuvvet ve peletleme kalıp sıcaklığı gibi kontrol parametreleri, pelet yoğunluğunu ve dolayısıyla enerji tüketimini etkiler. Optimal nem içeriği ve basınçla birleştirilmiş yüksek sıcaklıklar, pelet yoğunluğunu artırabilirken (Găgeanu et al., 2021), bu parametrelerin hassas kontrolü enerji verimliliğini sağlamada esastır.

4.2. Yanma Sistemlerinde Emisyon Kontrolü

Tarımsal pelet yakıtlarının yakılması sırasında ortaya çıkan emisyonlar (CO, NOx, PM2.5, vb.), hem insan sağlığı hem de çevre için olumsuz etkiler yaratabilir. Bu emisyonların etkin bir şekilde kontrol edilmesi, biyokütlenin sürdürülebilir bir enerji kaynağı olarak kabulünü artırmak için hayati öneme sahiptir.

Yanma Odası ve Hava Beslemesi Optimizasyonu: Pelet kazanlarında ve sobalarında, yanma odası tasarımı ve hava beslemesinin optimize edilmesi, emisyonları azaltmanın temelini oluşturur. Özellikle, çok katmanlı sekonder hava dağılımının optimize edilmesi, mısır sapı ve pirinç kabuğu peletlerinin yanmasından kaynaklanan NOx ve CO emisyonlarını düşürürken yanma verimliliğini artırabilir (He et al., 2022). Primer ve sekonder hava akışının doğru oranlarda dağıtılması, özellikle zorlamalı çekişli biyokütle sobalarında, karbon monoksit, azot oksitler ve partikül madde emisyonlarını optimize edebilir (Deng et al., 2020).

İleri Yanma Kontrol Sistemleri: Pelet sobaları, pelet kazanlarına kıyasla yakıt kalitesi varyasyonlarına daha duyarlı olup, bu durum düzensiz emisyonlara yol açabilir. Yakıt besleme hızının fırın sıcaklığı veya lambda sensörleri aracılığıyla kontrol edildiği gelişmiş yanma kontrol sistemleri, hem emisyonları azaltma hem de verimliliği artırma potansiyeli sunar. Yanma yoğunlaştırıcılarının uygulanması, odun ve tarımsal peletlerin yanmasında yanmamış kirletici emisyonlarında önemli düşüşler sağlayabilir (Horvat et al., 2021).

Yakıt Kalitesinin Etkisi: Peletin nem içeriği, uzunluğu ve ince partikül oranı gibi fiziksel özellikleri, yanma performansını ve emisyonları doğrudan etkiler. Optimal nem içeriği, daha düşük emisyonlara yol açarken, aşırı ince partiküllerin varlığı gaz salınımındaki varyasyonları artırarak emisyonları yükseltebilir. Bu nedenle, ENplus veya ISO 17225-2 gibi standartlar çerçevesinde yakıt kalitesinin iyileştirilmesi, emisyon kontrolü için kritik bir adımdır (Mack et al., 2022, p. 26842).

Katkı Maddeleri Kullanımı: Kül birikimi ve korozyonu azaltmak amacıyla kül önleyici katkı maddelerinin kullanımı, CO emisyonlarını düşürme potansiyeli sunabilir. Ancak, bu katkı maddelerinin NOx emisyonları üzerindeki etkisi yakıt türüne ve katkı maddesine göre değişiklik gösterebilir. Azot oksit emisyonlarını azaltmak için ise hava sınıflandırması gibi bilinen teknikler veya az miktarda inorganik tuzun katı katalizör olarak kullanılması değerlendirilmelidir (Mirowski et al., 2020, p. 83).

Ön İşlem ve Yakıt Dönüşümü: Biyokömür (torrefaction) teknolojileri, biyokütlenin termal ön işlemden geçirilmesiyle peletlerin enerji yoğunluğunu artırabilir ve böylece mevcut pulverize kömür santrallerinde kömürle birlikte yakılmalarını sağlayarak net karbondioksit emisyonlarında büyük azalmalar sağlayabilir. Torrefaction gibi ön işlemler, özellikle daha derin hava kademeleme ile NOx emisyonlarını ve yanmamış karbon salınımını azaltabilirken, kazan verimliliğini de artırır (Lee et al., 2020).

4.3. Süreç Entegrasyonu ve Atık Isı Geri Kazanımı

Pelet üretim tesislerinin ve biyokütle bazlı enerji sistemlerinin genel enerji verimliliğini artırmak için süreç entegrasyonu ve atık ısı geri kazanımı stratejileri büyük fırsatlar sunar. Bu yaklaşımlar, bir tesisteki enerji akışlarını optimize ederek, harici enerji ihtiyacını minimize eder ve çevresel etkiyi daha da azaltır.

Birleşik Isı ve Güç Sistemleri: Pelet üretim tesislerinde veya biyokütle yakma tesislerinde birleşik ısı ve güç sistemlerinin entegrasyonu, hem elektrik hem de ısı üretimine olanak tanır. Bu, toplam enerji verimliliğini önemli ölçüde artırır ve özellikle kurutma gibi prosesler için düşük dereceli ısı ihtiyacını karşılayabilir (Nhien et al., 2021).

Tesisler Arası Isı ve Kütle Değişimi: Farklı endüstriyel tesisler arasında ısı ve kütle değişimi ağlarının entegrasyonu, atık enerjinin ve kaynakların yeniden kullanımını teşvik eder (Isafiade, 2024). Bu, biyoenerji üretim tesislerinde genel kaynak verimliliğini artırmak için geniş ölçekli bir optimizasyon stratejisidir.

Baca Gazı Isı Geri Kazanımı: Biyokütle yakma sistemlerinden çıkan baca gazları, önemli miktarda atık ısı taşır. Bu ısının geri kazanılması, özellikle biyokütle kurutma veya diğer termal prosesler için kullanılabilir (Khan et al., 2022). Baca gazından elde edilen ısının membran distilasyonu gibi teknolojilerle entegrasyonu, biyogaz tesislerinde besin konsantrasyonunu ve proses suyu geri kazanımını sağlayarak ek faydalar sunabilir (Khan et al., 2022).

Holistik Entegrasyon Yaklaşımları: Biyokütleden türetilmiş sentez gazı saflaştırma süreçleri gibi entegre sistemlerde, atık ısı geri kazanımı ve ejektör teknolojisinin entegrasyonu, proses maliyetlerini düşürürken enerji verimliliğini önemli ölçüde iyileştirebilir (Bashiri et al., 2021). Süreç tasarımında bütünsel bir yaklaşım benimsemek, gizli enerji verimsizliklerini ortaya çıkarabilir ve sistem genelinde optimum performans sağlayabilir

5. Tarımsal Pelet Yakıtlarının Çevresel ve Ekonomik Etkileri

Tarımsal kaynaklı pelet yakıtlarının geniş ölçekli benimsenmesi ve sürdürülebilir bir enerji kaynağı olarak potansiyeli, çevresel performansları ve ekonomik uygulanabilirlikleriyle doğrudan ilişkilidir. Bu bölüm, yaşam döngüsü perspektifinden tarımsal peletlerin çevresel faydalarını ve zorluklarını incelerken, aynı zamanda pazar potansiyeli, maliyet etkinliği ve politika desteklerini de analiz etmektedir.

5.1. Yaşam Döngüsü Çevresel Performansı

Tarımsal pelet yakıtlarının çevresel performansı, esas olarak Yaşam Döngüsü Değerlendirmesi metodolojileri ile nicel olarak belirlenmektedir. Bu değerlendirmeler, hammaddenin tarladan toplanmasından, işlenmesine, peletlenmesine, taşınmasına ve son olarak enerji üretimi için yakılmasına kadar tüm aşamaları kapsar (Prasad et al., 2020).

Sera Gazı Emisyonları: Tarımsal peletlerin en önemli çevresel faydalarından biri, genellikle karbon nötr bir yakıt olarak kabul edilmeleridir. Biyokütle büyüme süreçlerinde atmosferden CO2 emer ve yandıklarında bu CO2'yi serbest bırakır. LCA çalışmaları, pelet üretimi ve taşınması sırasında kullanılan fosil yakıtlardan kaynaklanan emisyonları da dikkate alarak net bir sera gazı dengesi ortaya koyar (Ebadian et al., 2021). Odun peletlerinin fosil yakıtların yerine kullanılmasıyla sera gazı emisyonlarında önemli düşüşler elde edildiği belirtilmektedir (Sgarbossa et al., 2020). Tarım kaynaklı peletlerin sera gazı emisyon azaltım potansiyeli, iklim değişikliğiyle mücadelede önemli bir rol oynamaktadır (Nosenzo & Kelman, 2025, p. 1).

Diğer Çevresel Etki Kategorileri: Sera gazı emisyonlarının yanı sıra, LCA, asitlenme, ötrofikasyon, insan sağlığı üzerindeki partikül madde etkileri ve su kıtlığı gibi diğer çevresel

etki kategorilerini de değerlendirir (Rashedi et al., 2022). Tarımsal pelet üretimi ve kullanımında, bu kategorilerdeki etkiler hammadde türü, işleme teknolojileri ve lojistik zincire bağlı olarak değişiklik gösterir. Örneğin, tarımsal pelet biyoyakıtlarının üretimi için su kıtlığı endeksine en fazla katkı, hammadde toplama ve taşıma, ezme, eleme, yapıştırıcı ekleme, peletleme, soğutma ve son eleme gibi faaliyetlerden gelmektedir (Rashedi et al., 2022).

Arazi Kullanımı ve Biyoçeşitlilik: Biyoenerji ürünleri için arazi kullanımı, LCA çalışmalarında önemli bir konudur. Birinci nesil biyoyakıtlar, özellikle arazi kullanım değişiklikleri dahil edildiğinde, çevresel açıdan fosil yakıtlardan daha kötü performans gösterebilir. Ancak, tarımsal atıklar gibi ikinci nesil biyokütle kaynakları, gıda üretimiyle rekabet etmedikleri ve arazi kullanım değişikliklerine neden olmadıkları için bu tür çevresel baskıları azaltma potansiyeline sahiptir. Biyoenerji kullanımı, ekosistem hizmetleri ve biyoçeşitliliğin korunması gibi hedeflere katkıda bulunabilir (Englund et al., 2021, p. 2).

Su Kaynakları Üzerindeki Etkiler: Biyoyakıt üretimi, özellikle enerji mahsullerinin yetiştirilmesi için yüksek miktarda su gerektirebilir. Ancak tarımsal kalıntılardan pelet üretimi sırasında su ayak izi, özellikle yağlama yağı ve elektrik tüketimi gibi kalemlerden kaynaklanırken, buğday nişastası ve elektrik gibi girdilerin katkısı daha azdır (Rashedi et al., 2022).

5.2. Ekonomik Değerlendirme ve Pazar Potansiyeli

Tarımsal pelet yakıtlarının ekonomik uygulanabilirliği, üretim maliyetleri, pazar fiyatları, rekabet gücü ve politika destekleri gibi birçok faktöre bağlıdır.

Üretim Maliyetleri: Pelet üretim maliyetleri, hammadde temini, taşıma, ön işleme (kurutma, öğütme), peletleme ve depolama gibi bileşenlerden oluşur (Asif et al., 2024). Tarımsal atıkların hammadde olarak kullanılması, düşük maliyet avantajı sunsa da, hammadde kaynaklarının dağınık olması nedeniyle toplama, taşıma ve depolama maliyetleri üretim maliyetlerini artırabilir. Pelet üretiminde, bağlayıcı maliyeti, hammadde maliyeti ve işçilik maliyetleri gibi faktörler, üretim maliyetlerini önemli ölçüde etkilerken, pelet satış fiyatı ekonomik getiriyi en çok etkileyen faktördür (Asif et al., 2024).

Pazar Potansiyeli ve Fiyat Rekabetçiliği: Tarımsal peletler, özellikle endüstriyel ve konut sektörlerinde fosil yakıtlara alternatif olarak büyük bir pazar potansiyeline sahiptir. Ancak, küresel pelet pazarı genellikle odun peletleri tarafından domine edilmekte olup, tarımsal peletlerin bu pazarda yer edinebilmesi için fiyat rekabetçiliğini sağlaması gerekmektedir. Nosenzo ve Kelman, tarım kaynaklı peletlerin birçok pazarda geleneksel fosil yakıtlara karşı rekabetçi fiyatlar elde edebileceğini belirtmektedir (Nosenzo & Kelman, 2025).

Sosyo-ekonomik Faydalar: Tarımsal pelet üretimi, kırsal bölgelerde yeni istihdam fırsatları yaratma ve tarım sektörüne ek gelir sağlama potansiyeline sahiptir (Ebadian et al., 2021). Biyoenerji sektörünün gelişimi, enerji ve tarım gibi doğrudan ilgili sektörlerin yanı sıra, ulaştırma, ticaret, hizmetler ve imalat gibi dolaylı sektörlerde de istihdamı olumlu etkileyebilir (Roszkowska & Szubska-Włodarczyk, 2021, p. 76). Örneğin, bir tesisin tüm tedarik zinciri boyunca 2.477 iş yaratabileceği ve çiftçilere önemli gelir sağlayabileceği belirtilmiştir. Biyogaz teknolojisi, kırsal bölgelerde önemli sosyoekonomik etkiler göstermiş, ev ekonomilerinde yakıt maliyetlerini düşürerek tasarruf sağlamıştır.

Tedarik Zinciri Yönetimi: Tarımsal atıkların sürdürülebilir bir şekilde toplanması, depolanması ve pelet üretim tesislerine taşınması, etkin bir tedarik zinciri yönetimi gerektirir. Bu, lojistik maliyetlerini minimize etmek ve hammaddenin sürekli tedarikini sağlamak için kritik öneme sahiptir.

5.3. Sürdürülebilirlik Kriterleri ve Politika Destekleri

Tarımsal pelet yakıtlarının sürdürülebilir bir enerji çözümü olarak kabul görmesi ve yaygınlaşması, net sürdürülebilirlik kriterlerinin belirlenmesi ve destekleyici politikaların uygulanmasıyla mümkündür.

Sürdürülebilirlik Sertifikasyonları: Biyokütle yakıtlarının etik üretimi ve sürdürülebilirlik sorunlarını ele almak için sertifikasyon programları kritik rol oynamaktadır. Bu programlar, sosyal, çevresel ve kaynak verimliliği konularına dikkat ederek sürdürülebilir biyoenerji üretimine geçişi kolaylaştırmak amacıyla tasarlanmıştır. Avrupa Birliği'nde sürdürülebilir biyoenerji çözümleri, sürdürülebilirlik kriterlerine uymak zorundadır (Englund et al., 2021, p. 2).

Devlet Politikaları ve Teşvikler: Hükümet politikaları ve teşvik mekanizmaları, tarımsal pelet pazarının gelişiminde belirleyici bir role sahiptir. Biyoenerji stratejisinin önemli bir bileşeni olan politikalar, ekonomik çıkarları çevresel sürdürülebilirlikle uyumlu hale getiren bir çerçeve oluşturur (Rabbani et al., 2023, p. 698). Örneğin, Pakistan'da hükümet biyoyakıt sektörünü teşvik etmek için vergi muafiyetleri ve teşvikler getirmişken, Çin de mahsul kalıntılarına dayalı biyoenerjiyi desteklemek için önlemler almıştır. Ancak, yetersiz uzun vadeli planlama ve finansal destek gibi zorluklar da bulunmaktadır (Osman et al., 2024, p. 1141).

Döngüsel Biyoekonomi Entegrasyonu: Tarımsal atıkların biyoenerjiye dönüştürülmesi, döngüsel biyoekonominin önemli bir parçasıdır. Bu yaklaşım, atıkların azaltılması, yeniden kullanılması ve geri dönüştürülmesini vurgulayarak, tarımsal atık biyokütle yönetiminde stratejik bir rol oynar (Prado-Acebo et al., 2024). Örneğin, mantar yetiştirme atıklarının briket performansının optimize edilmesi, döngüsel ekonomi yaklaşımıyla değerlendirilmektedir. Tarımsal atıklardan elde edilen lignoselülozik biyokütle, biyoyakıtlar, biyo-kompozitler ve biyo-plastikler gibi çeşitli ürünlerin geliştirilmesi için sürdürülebilir bir kaynak sunar (Mujtaba et al., 2023).

Sosyal Kabul ve Bilinçlendirme: Yenilenebilir enerji projelerine geçiş, kamuoyunun ve etkilenen toplulukların muhalefetiyle karşılaşabilir. Bu nedenle, enerji geçiş projelerinde katılım ve eşitlik arasındaki bağlantılar hakkında incelikli bir anlayış gereklidir. Toplum katılımı ve şeffaf iletişim akışı, yerel halkın biyoenerji sistemlerine yönelik algısını olumlu yönde değiştirmede kritik öneme sahiptir. Enerji geçişinde karşılaşılan zorluklar arasında düzenleyici çerçeveler, mevcut altyapıyla entegrasyon ve kamu algıları gibi teknik olmayan faktörler de bulunmaktadır (Menghwani et al., 2022).

6. Sonuç ve Gelecek Perspektifleri

Bu derleme makalesi, tarım kaynaklı pelet yakıtlarının yaşam döngüsü değerlendirmesi ve emisyon-enerji optimizasyonu üzerine kapsamlı bir bakış sunmuştur. Analizler, tarımsal kalıntılardan elde edilen pelet yakıtlarının, fosil yakıtlara kıyasla önemli çevresel faydalar sağlama potansiyeline sahip olduğunu ve sürdürülebilir bir enerji geleceği için kritik bir rol oynayabileceğini göstermektedir (Nosenzo & Kelman, 2025, p. 1). Ancak, bu potansiyelin tam olarak gerçekleştirilmesi, hem üretim süreçlerinde hem de enerji dönüşüm sistemlerinde sürekli optimizasyon ve yenilikçi yaklaşımlar gerektirmektedir.

Yaşam Döngüsü Değerlendirmesi metodolojisi, tarım kaynaklı pelet yakıtlarının çevresel etkilerini bütünsel olarak anlamak için vazgeçilmez bir araçtır. LCA sonuçları, sera gazı emisyonlarının azaltılması başta olmak üzere, çeşitli çevresel etki kategorilerinde genellikle olumlu bir tablo çizmektedir (Sgarbossa et al., 2020). Ancak, LCA çalışmalarının kapsam, sistem sınırları ve veri kalitesindeki farklılıklar, sonuçların karşılaştırılabilirliğini

etkileyebilmekte ve bu alanda daha fazla standardizasyona ihtiyaç duyulmaktadır. Tarımsal atıkların "atık" tanımı, arazi kullanım değişiklikleri ve tahsisat yöntemleri gibi metodolojik kararlar, sonuçların yorumlanmasında kritik bir rol oynamaktadır (Pandey & Erbaugh, 2024).

Pelet üretim süreçlerinin enerji yoğunluğu ve yanma sırasında oluşan emisyonlar, bu teknolojilerin çevresel performansını belirleyen ana zorluklardır. Kurutma ve peletleme aşamalarında enerji verimliliğini artıran teknolojiler ve entegre sistemler (örneğin, atık ısı geri kazanımı, CHP uygulamaları), üretim sürecinin çevresel ayak izini önemli ölçüde azaltabilir (Bashiri et al., 2021; Ibrahim et al., 2025). Yanma sistemlerinde ise, primer ve sekonder emisyon kontrol stratejileri (yanma optimizasyonu, partikül filtreleri, NOx azaltma sistemleri), hava kalitesi üzerindeki olumsuz etkileri minimize etmek için elzemdir (He et al., 2022). Hammaddelerin karakteristik özelliklerinin (kül içeriği, alkali metal konsantrasyonu) iyi anlaşılması ve yönetilmesi, yanma verimliliğini artırmanın ve korozyon gibi operasyonel sorunları önlemenin temelini oluşturur (Nosenzo & Kelman, 2025, p. 1).

Ekonomik açıdan, tarımsal pelet yakıtlarının pazar potansiyeli yüksektir, ancak rekabetçilik fosil yakıt fiyatları, üretim maliyetleri ve hükümet politikaları tarafından şekillenmektedir. Yerel istihdam yaratma ve kırsal ekonomilere katkı sağlama potansiyeli, bu yakıtların sosyal faydalarını artırmaktadır (Ebadian et al., 2021). Sürdürülebilirlik sertifikasyonları ve destekleyici politikalar, sektörün gelişimini teşvik etmek ve tüketicinin güvenini sağlamak için hayati öneme sahiptir. Ancak, sürdürülebilirliğin sosyal boyutu henüz ekonomik ve çevresel boyutlar kadar detaylı incelenmemiştir (Svensson et al., 2024).

Gelecek Perspektifleri

Tarımsal pelet yakıtlarının geleceği, aşağıdaki alanlarda yapılacak araştırmalar ve gelişmelerle şekillenecektir:

İleri Proses Teknolojileri: Yüksek pelet kalitesi elde etmek için işleme metodolojilerinin iyileştirilmesi, özellikle geleneksel olmayan biyokütlelerden ve enerji tüketimini azaltarak fiziki pelet kalitesini optimize eden teknolojiler üzerinde daha fazla araştırma ve geliştirme gerekmektedir. Özellikle kırsal toplulukların ekonomisini desteklemek ve enerji bağımsızlığını sağlamak için katkısız ve ön işlem gerektirmeyen küçük ölçekli pelet üretiminin geliştirilmesi önemlidir. Çeşitli biyokütle kaynakları ve ortak peletleme teknolojileri ile biyokütle enerjisinin daha iyi ve daha verimli kullanılması gereklidir (Cui et al., 2021).

Döngüsel Biyoekonomi Entegrasyonu: Tarımsal atıklar, biyoyakıtlar, biyo-kompozitler ve biyo-plastikler gibi geniş bir ürün portföyü geliştirmek için lignoselülozik biyokütle kaynakları sağlamaktadır (Mujtaba et al., 2023). Tek tek proseslerin karlılığı düşük olduğundan, tüm biyokütle fraksiyonlarını sıfır atık yaklaşımıyla kullanan entegre çoklu besleme stoğu ve çoklu ürün biyolojik rafineri şemaları daha iyi bir alternatiftir. Döngüsel ekonomi, tarımsal atık biyokütle yönetiminde ve agro-endüstriyel atıkların değerli ürünlere dönüştürülmesinde anahtar bir stratejik yaklaşımdır (Đorđević et al., 2024). Bu yaklaşım, atıkların azaltılması, geri dönüşümü, geri kazanımı, yeniden kullanımı ve yenilenmesini vurgulayarak, gıda ve tarım sektöründe sürdürülebilirliği artırmayı hedeflerken, ekonomik değer temelli bir perspektifle maliyetler, faydalar ve dağıtım etkileri dengelenmelidir. Tarımsal artık atıklar, düşük maliyetle ve bol miktarda bulunabilen bir hammadde kaynağı olarak ekonomik kazanç için etkin bir şekilde değerlendirilebilir ve daha temiz yakıtlar gibi katma değerli ürünler üretilebilir (Sharma et al., 2024).

Politika ve Pazar Mekanizmalarının Geliştirilmesi: Tarımsal peletlerin tam potansiyelini ortaya çıkarmak için hedeflenmiş yatırımlar, teknolojik gelişmeler ve destekleyici politikalar gereklidir. Ürün tutarlılığını sağlamak, mevcut enerji sistemlerine entegrasyonu kolaylaştırmak

ve güvenilir tedarik zincirlerinin geliştirilmesini desteklemek için pelet üretimi ve kalite güvencesi için açık teknik standartların oluşturulması kritik öneme sahiptir. İthalatçı ülkelerin yerel biyokütle tüketim teşvikleri ve sürdürülebilirlik kriterleri, pelet ihracatını önemli ölçüde artırmaktadır. Biyoenerji projelerinin başarısı için uluslararası paydaşlar arasında işbirliği ve eşgüdüm hayati önem taşımaktadır (Svensson et al., 2024).

Teknolojik Gelişmeler: Daha iyi emisyon kontrolü için yakıt tasarımı ve soba teknolojisinde sürekli araştırma ve geliştirme önerilmektedir. Pelet sıcaklığı ve kalıp içinde kalış süresi gibi işlem parametrelerinin optimize edilmesi, fiziki pelet kalitesini iyileştirirken enerji tüketimini azaltabilir (Benders et al., 2025).

Sonuç olarak, tarım kaynaklı pelet yakıtları, yenilenebilir enerji portföyünün ayrılmaz bir parçası olarak, enerji güvenliği ve iklim değişikliğiyle mücadelede önemli katkılar sunmaktadır. Bilimsel ve mühendislik tabanlı optimizasyon yaklaşımlarının sürekli uygulanması, bu yakıtların çevresel faydalarını maksimize ederken, ekonomik uygulanabilirliğini ve toplumsal kabulünü artıracaktır. Gelecekteki araştırmalar ve politika destekleri, tarım kaynaklı pelet yakıtlarının sürdürülebilir enerji dönüşümündeki rolünü daha da pekiştirecektir.

Yapay Zekâ Katkı Beyanı

Bu çalışmanın yazım sürecinde, yalnızca dil düzenleme, yazım kuralları, açıklık ve akıcılığın artırılması gibi amaçlarla yapay zekâ temelli yazılım programlarından yararlanılmıştır.

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KÜÇÜK ÖLÇEKLİ, TEK EKLEMLİ MANYETİK TERS TEK SARKAÇ MEKANİZMASININ BİLGİSAYAR DESTEKLİ BENZETİMİ

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ÖZET

Teknolojideki son gelişmeler, yumuşak robot teknolojilerinin biyomedikal alanlarda kullanımını önemli ölçüde artırmıştır. Bu sistemler esnek yapıları sayesinde canlı dokulara zarar vermeden etkileşime girebilmekte ve minimal invaziv cerrahi, ilaç taşıma ve mikro manipülatör gibi alanlarda önemli avantajlar sağlamaktadır. Manyetik alanla kontrol edilen yumuşak robotlar ise temassız ve uzaktan hassas yönlendirilebilmeleri sayesinde bu alanda öne çıkan bir çalışma konusudur. Bu çalışmada, biyomedikal uygulamalarda kullanılmak üzere manyetik alanla kontrol edilen, küçük ölçekli ve tek eklemli bir manyetik ters sarkaç mekanizmasının matematiksel modeli oluşturulmuş ve MATLAB/Simulink ortamında oransal-integral-türevsel denetleyici (proportional-integral-derivative, PID) kontrollü sayısal benzetimi gerçekleştirilmiştir. Öncelikle sistem yalnızca yerçekimi etkisi altında test edilerek mekanik modelin fiziksel doğruluğu kontrol edilmiştir. Ardından manyetik tork ve kuvvet etkileri, sönüm katsayısı, sarım sayısı ve akım gibi parametrelerin değiştirilmesiyle sistem incelenmiştir. İnceleme sonucunda, sönüm katsayısının azalmasının salınım süresini uzattığını; sarım sayısı ve akım artışının ise manyetik momenti yükselterek sistemin daha hızlı ve kararlı tepki verdiğini göstermiştir. Ardından sistemin kararlılığını incelemek için PID kontrol sistemine referans değer girilmiş ve sarkacın referans değerine yakınsadığı gözlemlenmiştir. Elde edilen sonuçlar, hem mekanik hem de elektromanyetik modelin doğru şekilde tanımlandığını ve sistemin istenilen dinamik özellikleri yansıttığını ortaya koymuştur. Geliştirilen bu model, gelecekte manyetik manipülatör sistemlerinin gelişmiş kontrol algoritmaları ve konum takip yöntemleriyle birleştirilerek biyomedikal alanda kullanılabilecek yüksek hassasiyetli, uzaktan kontrollü robotik sistemlerin geliştirilmesine temel oluşturmaktadır.

Anahtar Kelimeler: Sarkaç, Manyetik Sarkaç, PID Kontrol, Yumuşak Robot, Mikro Robot

COMPUTER-AIDED SIMULATION OF A SMALL-SCALE, SINGLE-JOINT MAGNETIC INVERTED PENDULUM MECHANISM

ABSTRACT

Recent technological advancements have significantly expanded the utilization of soft robotic technologies in biomedical applications. Due to flexible structures, soft robotic systems can interact with living tissues without causing damage and provide major advantages in minimally invasive surgery, targeted drug delivery, and micro-manipulation. Magnetically actuated soft robots have gained prominence in this field because of their ability to be remotely and precisely controlled without physical contact. The present study developed a mathematical model of a small-scale, single-joint magnetic inverted pendulum mechanism actuated by a magnetic field and performed a proportional–integral–derivative (PID) controlled numerical simulation in the MATLAB/Simulink environment for potential biomedical applications. The system was initially examined under gravitational effects only to validate the physical accuracy of the mechanical model. Subsequently, variations in magnetic torque and force, damping coefficient, number of coil windings, and electric current were analyzed to evaluate system performance. Simulation results indicated that a lower damping coefficient extended oscillation duration, whereas higher number of coil windings and current increased the magnetic moment, yielding faster and more stable responses. The findings confirmed that both the mechanical and electromagnetic models were accurately defined and successfully represented the intended dynamic behavior. The developed model establishes a foundation for future studies combining advanced control algorithms and position-tracking methods to design high-precision, remotely controlled magnetic manipulator systems for biomedical applications.

Keywords: Pendulum, Magnetic Pendulum, PID Control, Soft Robot, Micro Robot

1. GİRİŞ

Teknolojik gelişmeler, insan hayatını kolaylaştırmak ve yaşam kalitesini arttırmak için birçok alanda yeni çözümler oluşturmuştur. Bu amaçla geliştirilen robotik sistemler, otomotiv, beyaz eşya, savunma sanayi gibi endüstriyel sanayiden günlük yaşama kadar pek çok farklı alanda kullanılmaya başlanmıştır (Singh ve Banga, 2022; Urrea ve Kern, 2025; Palčič ve Prester, 2024). Son yıllarda biyomedikal alanındaki gelişmelerle birlikte, geleneksel robotların tıp ve cerrahi uygulamalarında kullanımı artmıştır. Bu robotlar, hassas cerrahi işlemler, rehabilitasyon cihazları ve minimal invaziv girişimler gibi alanlarda büyük avantajlar sağlasa da sert malzemelerden üretilmiş olmaları nedeniyle canlı dokularla etkileşimde yetersiz kalmaktadır. Canlı vücudu içerisinde hareket edebilecek, dokuya zarar vermeyecek ve uyum sağlayabilecek esnek sistemlere olan ihtiyaç araştırmacıları yeni robotik çözümler geliştirmeye yönlendirmiştir. Bu bağlamda, yumuşak (soft) robotlar ön plana çıkmıştır (Chatterjee ve diğerleri, 2024; Chaparro-Cárdenas ve diğerleri, 2018; Kim ve diğerleri, 2018; Minig ve diğerleri, 2017).

Yumuşak robotlar, biyolojik sistemlerden ilham alınarak geliştirilmiş esnek ve uyumlu malzemelerden üretilen robotik sistemlerdir. Kullanılan malzemelerin elastisite modülü 10^4 ile 10^9 Pa arasında olup, bu değerler biyolojik malzemelerin mekanik özelliklerine yakındır (Kim ve Zhao, 2022). Araştırmacılar tarafından en çok kullanılan tanım Cianchetti ve ekibi tarafından 2015 yılında şu şekilde verilmiştir: Çevreyle aktif olarak etkileşime girebilen ve doğal veya yapısal uyuma bağlı olarak büyük deformasyonlara uğrayabilen yumuşak robotlar-cihazlardır (Cianchetti ve diğerleri, 2015).

Yumuşak robotların kontrol yöntemi kullanım alanı ve ihtiyaca göre değişiklik göstermektedir. Güç ihtiyacının yüksek olduğu uygulamalarda pnömatik (Decroly ve diğerleri, 2021) ve hidrolik (Tilvawala ve diğerleri, 2021) kontrol yöntemleri kullanılırken, hassas ve küçük boyutlu sistemlerde manyetik alan (Yang ve diğerleri, 2024), elektrik alan (Guo ve diğerleri, 2021; Duduta ve diğerleri, 2017) ve ışık (Cunha ve diğerleri, 2020) ile kontrol edilirler.

Yumuşak robotlar geleneksel robotlara göre birçok avantaj sağlar. Özellikle biyomedikal uygulamalarda yumuşak robotların çevre ile etkileşime girebilmesi, kuvvetleri geniş alanlarda eşit dağıtarak doku hasarını minimize etmesi minimal invaziv gibi operasyonlarda insan dokusuna zarar vermeden güvenli bir şekilde çalışmayı sağlar. Esnek ve karmaşık yapısı ile düzensiz yüzeylere uyum sağlar, çok yönlü kullanıma açıktır. Bir diğer önemli avantajı ise biyouyumlu malzemelerden üretilir olmasıdır. Hidrojel, elastomer gibi esnek ve vücut dostu malzemeler bu robotların temel malzemeleridir.

Öte yandan, yumuşak robotlar yük kapasiteleri sınırlı olmasına karşın, canlı dokulara temasta avantaj oluşturan hassas hareket kabiliyeti sunarlar, güç yüklemezler. Sonsuz serbestlik derecesine sahip olmaları nedeniyle yumuşak robotların tasarımında matematiksel ve sayısal modelleme yapılır. Böylelikle hassas ve daha fazla kontrol edilebilir hale gelirler (Ashuri ve diğerleri, 2020). Ayrıca yapay zeka tabanlı kontrol stratejileri, robotların davranışlarını tahmin etme ve çevresel koşullara dinamik olarak uyum sağlama yeteneklerini geliştirerek, yumuşak robotların etkileşim kabiliyetini ve hareket hassasiyetini önemli ölçüde arttırır (Cao ve diğerleri, 2024).

Manyetik yumuşak robotlar, manyetik alanlar altında şekil değiştirebilme yeteneğine sahip esnek, yumuşak robotlardır. Kompozit bir malzeme yapısına sahiptirler. Manyetik katkıların yumuşak polimerik matrislere gömülmesiyle oluşturulurlar. Manyetik alan uygulandığında uzaktan kontrol edilerek hızlı ve kontrollü bir şekilde şekil değiştirir ve çevresiyle etkileşime girerler. Bu özellik onları biyomedikal uygulamalarda son derece önemli kılar (Mao ve

diğerleri, 2022; Wang ve diğerleri, 2020; Ke ve diğerleri, 2024). Minimal invaziv cerrahi müdahaleler (Jin ve diğerleri, 2023; Chautems ve diğerleri, 2019), ilaç taşıma sistemleri (Zheng ve diğerleri, 2023) ve hassas tıbbi uygulamalar (Ye ve diğerleri, 2022; Kim ve diğerleri, 2022) gibi alanlarda kullanılabilecek farklı görevler için büyük potansiyele sahiptirler.

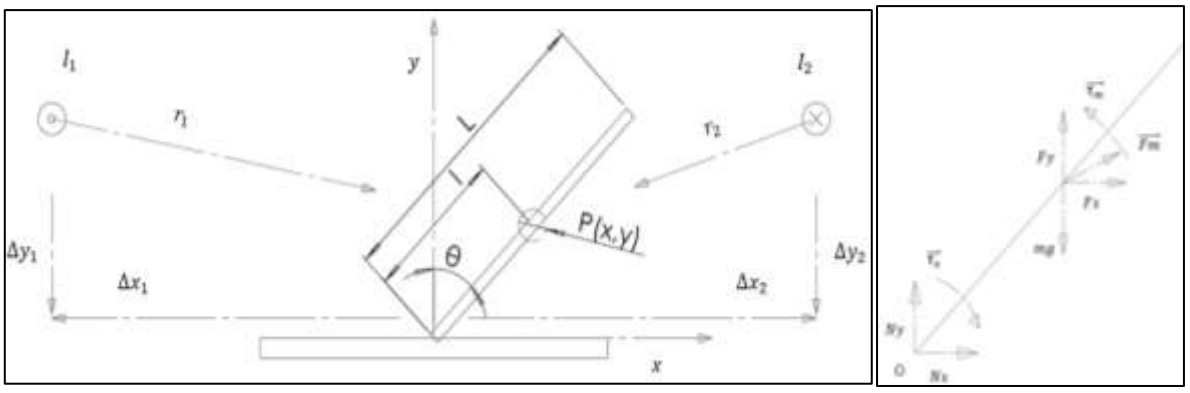
Manyetik yumuşak robotların avantajları arasında temassız uzaktan kontrol edilebilme, çok yönlülük, düşük güç tüketimi, hafiflik hatta ısı üretimine varan özellikleri bulunmaktadır. Ayrıca yuvarlanma, emekleme (Hu ve diğerleri, 2018) ve yüzme (Huang ve diğerleri, 2019) gibi farklı hareket modları gerçekleştirerek çevresel koşulları aşabilme yeteneğine sahiptirler. Ancak manyetik alanla istenilen şekilde hareket edebilmesi için, robotların malzeme yapısındaki manyetik partiküllerin dağılımı, yönlendirilmesi ve hareket kontrolü gibi faktörlerin optimize edilmesi gerekmektedir. Bu noktada, matematiksel modelleme ve yapay zeka tabanlı stratejiler, robotların etkinliğini ve hassasiyetini artırmak için kritik rol oynamaktadır. Ayrıca çevresel faktörler, manyetik alanın etkisini sınırlar ve robotun beklenen performansını etkiler (Wu ve diğerleri, 2020).

Bu çalışmada yumuşak robotlarda kullanılmak üzere manyetik alanla çalışan tek eksenli bir robot parmak mekanizmasının (sarkaç) kavramsal tasarımı, matematiksel modeli ve bilgisayar destekli benzetimi yapılmıştır. İlk bölümde literatür taraması ve manyetik yumuşak robotlar hakkında genel bilgiler verilmiştir. İkinci bölümde sarkaç model için mekanik ve manyetik alan denklemleri paylaşılmıştır. Üçüncü bölümde Matlab/Simulink ile benzetim çalışmaları yapılıp yorumlanmıştır. Dördüncü bölümde sonuçlar paylaşılıp gelecekte yapılabilecek çalışmalar için tavsiyeler verilmiştir.

2. MATERYAL VE YÖNTEM

Şekil 2.1. a) manyetik sarkaç modelinin kesit görünüşünü vermektedir. Uzunluğu 2L olan sarkaç, x-y düzleminde dönme hareketi yapabilmektedir ve bu düzlemde y ekseniyle θ açısı oluşturmaktadır. Sarkaç manyetik özelliklere sahip olup, bu özelliklerin tümünün sarkacın kütle merkezinde toplandığı varsayılmaktadır. Manyetik özellik, m ile gösterilen bir manyetik dipol momenti ile tanımlanır.

Sistemin kontrolü, koordinat düzleminde yer alan $x_1y_1z_1$ ve $x_2y_2z_2$ noktalarına yerleştirilmiş sonsuz uzunlukta çizgisel bobinler aracılığıyla sağlanmaktadır. Bu bobinlerden sırasıyla I_1 ve I_2 akımları geçirilmektedir. Kütlesi M olan çubuk, koordinat başlangıç noktası olan (0,0) konumundan sonra dönme serbestliğine sahiptir. Çubuğun, y ekseniyle yaptığı açı θ ile tanımlanır ve bu çubuğun orijine göre atalet momenti J olarak alınmaktadır.



a) b)

Şekil 2.1. a) problemin tanımı, b) serbest cisim diyagramı

Tablo 2.1. Problemin tanımı

Parametre	Değer	Açıklama
L (m)	0.02	Sarkaç uzunluğu
l (m)	0.01	Kütle merkezi uzunluğu
M (kg)	0.005	Sarkaç kütlesi
θ (Derece)	10°	Sarkaç açısı (sarkaç ve Y ekseni arasındaki açı)
I (A)	2	Kontrol akımı
N	200	Bobin sarım sayısı
m ($A.m^2$)		Mıknatıs manyetik dipol momenti
$\Delta x, \Delta y$		Bobin sargısının bulunduğu yarıçap
J (kg.m^2)		Sarkaç uç noktasına göre atalet momenti
x, y		Sarkacın ağırlık merkezinin koordinatları
F (N)		Manyetik kuvvetler
T (N.m)		Tork

Kabuller:

1. Çubuk homojen ve $\vec{m}$ manyetik dipol momentine sahiptir.
2. Bobini N sarım sayısına sahip olupi koorinat merkezinden Δ_x, Δ_y mesafelerinde konumlandırılmıştır.

2.1. Mekanik Etkilerin Hesabı

Cisme etki eden mekanik etkilerin hesabı için Newton denklemleri yazılır. O noktasına göre moment alınır.

$$\sum M_o = J.\ddot{\theta} \quad (1)$$

$$T_m - T_s - mglcos\theta - {F_x}^m lsin\theta + {F_y}^m lcos\theta = J.\ddot{\theta} \quad (2)$$

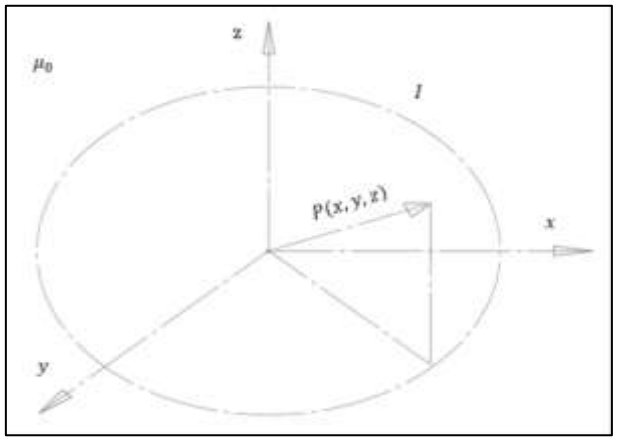
Burada dikkat edilir ise $T_m, {F_x}^m$ ve ${F_y}^m$ manyetik alana bağlı büyüklüklerdir. Bu nedenle manyetik alanı biliyorsak bu denklem sarkaç hareketini modellemeye yetecektir.

Eşitlik 2 düzenlenir ise manyetik sarkacın hareketini yöneten kısmi diferansiyel denklem elde edilir (Eşitlik 3). Eşitlik 3 ve Eşitlik 4 denklemlerinin birlikte çözümü sarkacın zamana bağlı davranışını vermektedir.

$$\ddot{\theta} = \frac{1}{J}\left[T_m - b.\dot{\theta} + mglsin\theta - {F_x}^m lsin\theta + {F_y}^m lcos\theta\right] \quad (3)$$

$$\dot{\theta} = \frac{d\theta}{dt} \quad (4)$$

2.2. Silindirik Koordinatlarda Boşluktaki Bobin İçin Manyetik Alan Hesabı



Şekil 2.2.1. silindirik koordinat sistemi

Sistemin ana davranışı Maxwell denklemleri ile hesaplanır.

$\nabla . \vec{E} = \frac{\rho}{E_0}$ (Gauss yasası) (5)

$\nabla x \vec{E} = -\frac{\partial B}{\partial t}$ (Faraday yasası) (6)

$\nabla x \left(\frac{1}{\mu} B\right) = \vec{J} + \varepsilon \frac{\partial \vec{E}}{\partial t}$ (Maxwell – Ampere yasası) (7)

Yukarıdaki Maxwell denklemleri vektörel formda verilmiştir. Burada;

∇: Nabla operatörü,

ρ: Yük yoğunluğu,

ε: Dielektrik permabiliti,

μ: Manyetik permabiliti,

$\vec{E}$: Elektrik alan vektörü,

$\overrightarrow{B}$: Manyetik alan vektörü,

$\vec{J}$: Elektrik akım yoğunluğunu ifade etmektedir.

Vektörel formda bulunan denklemler istenilen koordinat ekseninde yazılarak çözüm aranır.

Kartezyen koordinatlarda r_0 yarıçapına sahip içinden I akımı geçen bir bobinin manyetik alan bileşenleri, bobin merkezine göre;

$B_x = \frac{C\ x\ z}{2\ \alpha^2 B \rho^2}[(r_0{}^2 + r^2)E(k^2) - \alpha^2 K(k^2)]$
(8)

$B_y = \frac{y}{x} B_x = \frac{C\ y\ z}{2\ \alpha^2 B \rho^2}[(r_0{}^2 + r^2)E(k^2) - \alpha^2 K(k^2)]$ (9)

$B_z = \frac{C}{2\ \alpha^2 B}[(\alpha^2 - r^2)E(k^2) + \alpha^2 K(k^2)]$
(10)

Burada;

x,y,z: Kartezyen koordinatlarda hesaplanacak nokta (bobin merkezine göre), r_0: Bobin sarım yarıçapı, I: akım, μ_0: Boşluğun manyetik permabilitisi ($4\pi 10^{-7}$),N: Sargı sayısını göstermektedir.

Bu formüller, NASA tarafından yayımlanan "Simple Analytic Expressions for the Magnetic Field of a Circular Current Loop" başlıklı çalışmadan alınmıştır. Formüller, sabit akım durumunda geçerlidir. Manyetik alan $\vec{B}$ vektörü bilindiğine göre (Denklem 9) uzayda bulunan bir manyetik dipol $\vec{m}$ 'ye uyguladığı döndürme momenti (T/tork) ve kuvvet hesaplanır.

$$T = \vec{m}x\vec{B} \tag{11}$$

$$F = \vec{m}.\nabla\vec{B} \tag{12}$$

Sarkacın dönme serbestliği z ekseni etrafında olup, xyz eksenlerinde doğrusal hareketi sınırlandırılmıştır.

$$\vec{B}(x,z) = B_x\vec{\imath} + B_z\vec{k} \tag{13}$$

$$\vec{m} = m_x\vec{\imath} + m_z mz\vec{k} \tag{14}$$

$$T = [m_z B_x - m_x B_z]\vec{\jmath} \tag{15}$$

Yukarıdaki denklemde sadece y ekseninde döndürme momenti uygulandığı anlaşılmaktadır.

$$F = \left(mx\frac{\partial Bx}{\partial x} + mz\frac{\partial Bx}{\partial z}\right)\vec{\imath} + \left(mx\frac{\partial Bz}{\partial x} + mz\frac{\partial Bz}{\partial z}\right)\vec{k} \tag{16}$$

$$\vec{F} = F_x\vec{\imath} + F_z\vec{k} \tag{17}$$

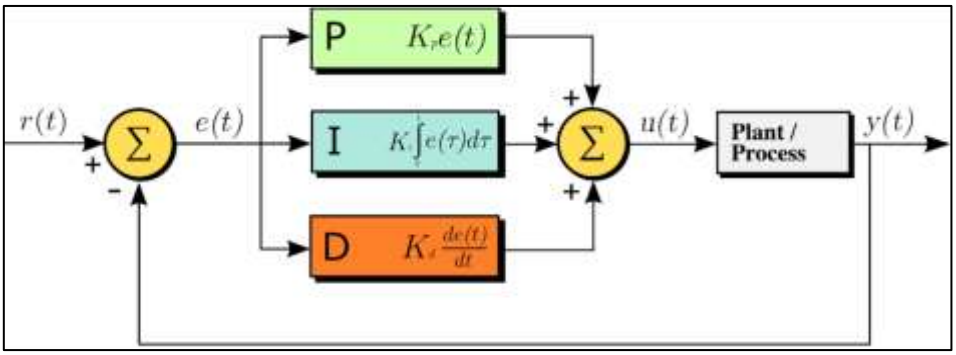
Böylelikle $\vec{T}$ ve $\vec{F}$ vektörleri hesaplanır. I akımı kontrol edilerek sarkacın konumu kontrol edilir.

2.3. Kontrolcü Tasarımı

Mekanik sistemler için birçok kontrolör mevcuttur. En yaygın olarak PID (oransal-integral-türevsel) kontrolör kullanılmaktadır. Kontrol yapısında hata sinyali e, referans açı θ_r ile mevcut açı θ arasındaki fark olarak tanımlanır. Kontrolcüden çıkan akım I_c hata sinyalinin değeri ile hatanın türevi ve integrali dikkate alınarak hesaplanır. Denklem 18 ve 19 bu kısmı ifade etmektedir. PID kontrol sistemlerinde kontrol karakteristiğini belirleyen K_p oransal, K_i integral ve K_d türevsel katsayılar bulunur. Bu katsayıların başlangıç değerinin bulunmasında Ziegler-Nichols yöntemi sıklıkla kullanılır (Yıldız ve diğerleri,2025).

$$e = \theta_r - \theta \tag{18}$$

$$I_c = K_p e + \frac{de}{dt}K_d + K_i \int e.dt \tag{19}$$

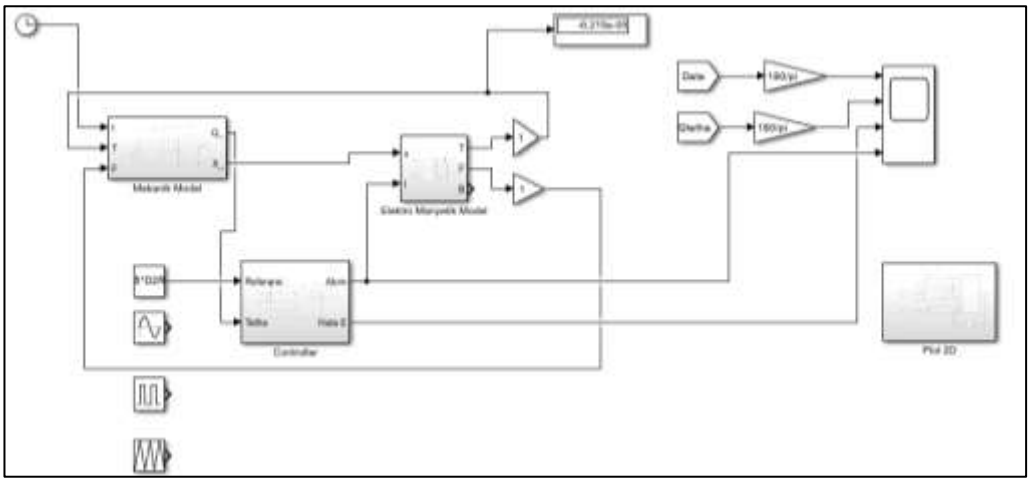


Şekil 2.3.1. PID kontrol algoritması

Kontrolcü tasarımı ile sarkacın istenilen konuma yakınsaması mümkün hale gelmiştir.

3. BULGULAR VE TARTIŞMA

Şekil 3'te benzetim programının Matlab/Simulink ara yüzü görünümü verilmiştir. Program 3 ana bileşenden oluşan bir yapıdadır. Elektro manyetik model bölümünde manyetik kuvvetlerin hesabı ile manyetik tork değerini hesaplamaktadır. Mekanik model ise zamana ve oluşan manyetik torka bağlı olarak sarkacın konumunu ve açısını hesaplamaktadır. Kontrolcü kısmı ise PID kontrolü gerçekleştirip sarkacın istenilen referans değerine ulaştırmaktadır.



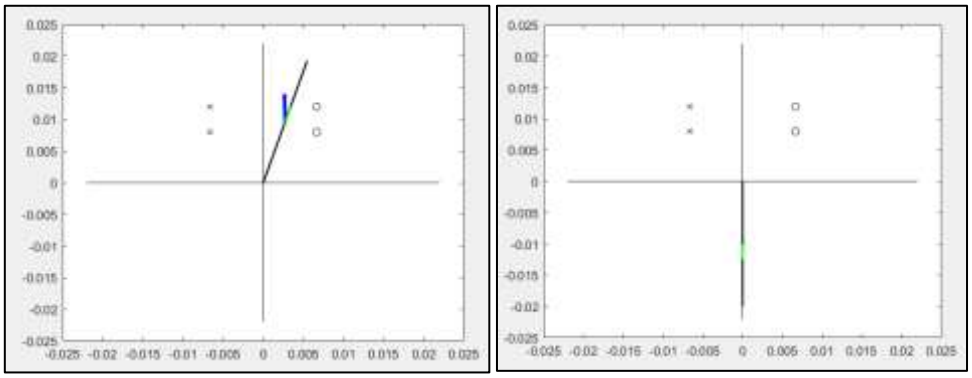
Şekil 3.1. Matlab/Simulink blok gösterimi

Benzetim çalışmalarında kullanılan fiziksel büyüklükler ve değerleri Tablo 2 ile verilmiştir. Benzetimler 3s boyunca 0.001s sabit adımla gerçekleştirilmiş olup, integrasyon işlemleri için matlab kütüphanelerinde yer alan 4. derece Runge-Kutta metodu kullanılmıştır.

Tablo 3.1. Fiziksel büyüklükler

Sembol	Değer	Birim	Açıklama
D_{X1}	0.006	m	1. bobinin x koordinatı
D_{X2}	0.006	m	2. bobinin x koordinatı
D_{y1}	0.008	m	1. bobinin y koordinatı
D_{y2}	0.012	m	2. bobinin y koordinatı
b	1e-5	N.m.s/rad	Sürtünme kuvveti
μ_0	4π e-07	H/m	Boşluğun manyetik geçirgenliği

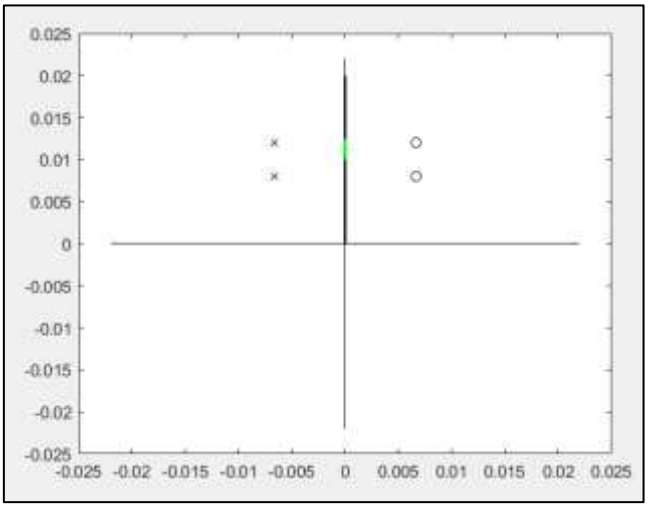
3.1. Sarkaç Sonuçları



a) b)

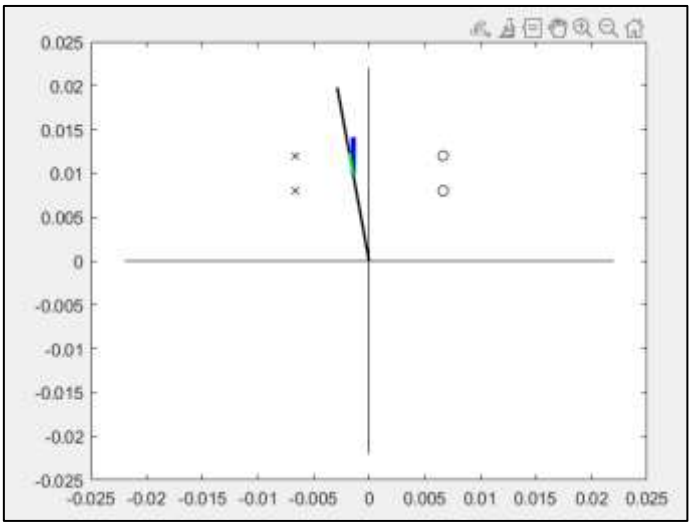
Şekil 3.1.1. a) sarkaç başlangıç durumu, b) sarkacın son durumu

Şekil 3.1.1.a)'da sarkaç sistemi başlangıçta +y ekseniyle 10° açı yapacak şekilde konumlandırılmış ve manyetik tork ile manyetik kuvvet sıfır kabul edilmiştir. Bu durumda yalnızca yerçekimi kuvveti etkili olmaktadır. Simülasyon sonucunda 3.1.1. b) sarkaç, yerçekimi momenti etkisiyle denge konumundan saparak -y eksenine doğru devrilmiştir. Bu davranış, sistemin fiziksel gerçeklikle uyumlu olduğunu ve mekanik modelin doğru şekilde çalıştığını göstermektedir.



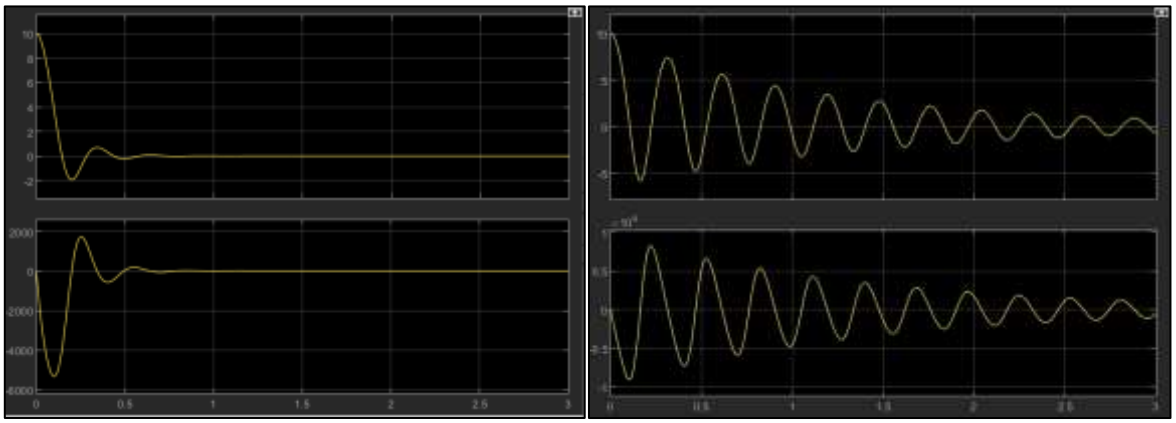
Şekil 3.1.2. açı 0° değerindeyken sarkaç modeli

Başka bir durumda ise sarkaç başlangıç açısı 0° olarak denenmiştir, +y ekseni doğrultusunda dik konumda başlatılmıştır. Sistemde manyetik tork ve manyetik kuvvet sıfır alınmış; yalnızca yerçekimi etkisi altındadır. Bu durumda sarkaç, yerçekimi kuvveti doğrultusuyla aynı eksende bulunduğundan herhangi bir net moment oluşmamış ve sistem, başlangıç durumunu koruyarak hareketsiz kalmıştır.

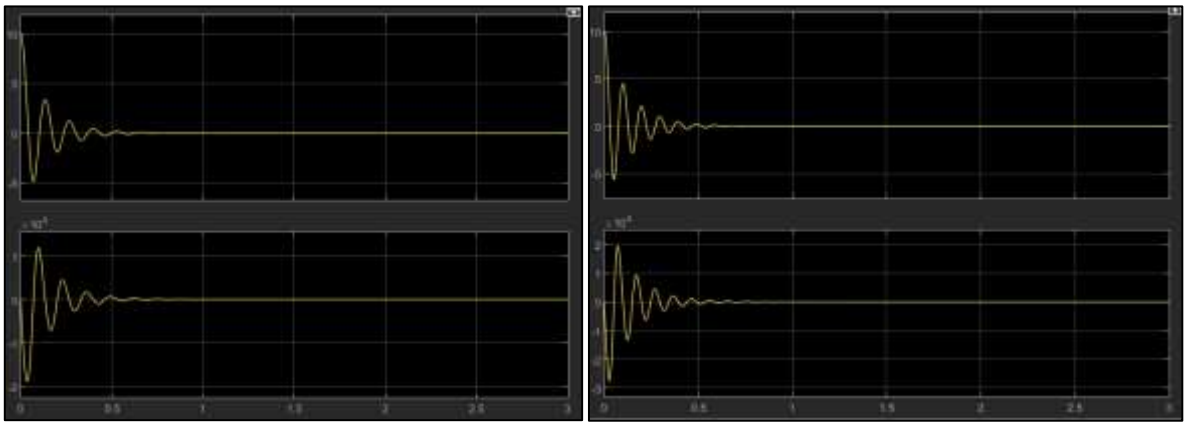


Şekil 3.1.3. açı -10° değerindeyken sarkaç modeli

Başlangıç açısı -10° olarak verildiğinde, sarkacın simülasyona y ekseninin sol tarafından başladığı gözlemlenmiştir. Bu durum, açının yönünün fiziksel modelde doğru tanımlandığını göstermektedir.



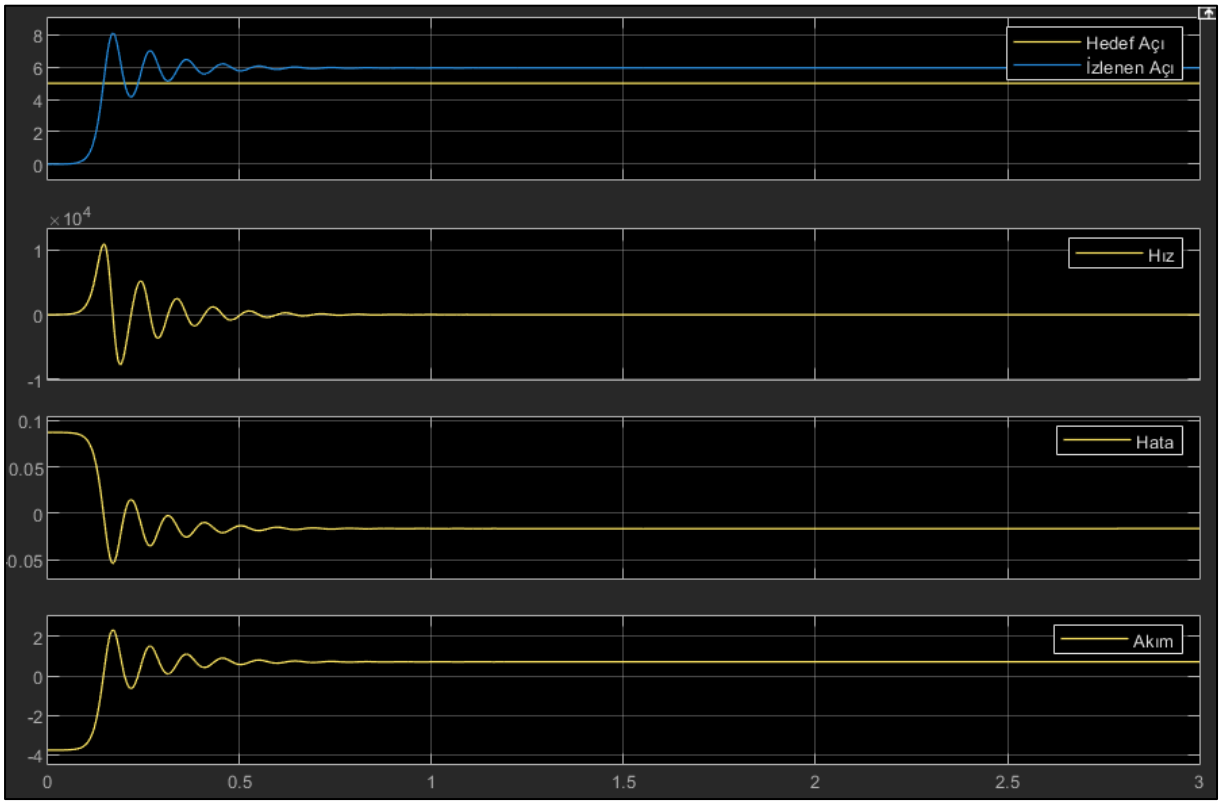
a) **b)**



c) **d)**

Şekil 3.1.4. a) sönüm katsayısı b=1e-5, sarım sayısı N:200, durağan sistem akımı I:1, b) sönüm katsayısı b=1e-6, c) sarım sayısı N:500, d) durağan sistem akımı I:4

Şekil 3.1.4.'de, ters sarkaç sisteminin farklı manyetik ve mekanik parametreler altındaki dinamik davranışı incelenmiştir. Her bir şekilde ilk grafik açıyı, ikinci grafik ise açısal hızı göstermektedir. Şekil 3.1.4. a), referans durum olarak belirlenmiş olup, sönüm katsayısı b=1e-5, sarım sayısı N=200 ve durağan sistem akımı I=1 A olarak alınmıştır. Şekil 3.1.4. b)'de yalnızca sönüm katsayısı b=1e-6 olarak azaltılmış ve sistemin daha az dirençle daha uzun süre salınım yaptığı gözlemlenmiştir. Bu durum, sönümleme katsayısının sistemin kararlılığı ve enerji kaybı üzerindeki etkisini açıkça göstermektedir. Şekil 3.1.4. c)'de ise yalnızca sarım sayısı artırılarak N=500 yapılmış ve manyetik torkun büyüklüğündeki artışla birlikte sistemin daha hızlı ivmelendiği görülmüştür. Sarım sayısındaki bu artış, oluşturulan manyetik momenti doğrudan etkilemiştir. Şekil 3.1.4. d)'de ise sadece akım değeri I=4 A seviyesine çıkarılmıştır. Bu durumda, sabit sarım sayısına rağmen manyetik kuvvetin ve torkun büyümesi nedeniyle sarkaç sisteminin çok daha güçlü bir tepki verdiği tespit edilmiştir.



Şekil 3.1.5. sarkaç modelini sabit 5° açı değerinde kontrolcü çalışması

Son olarak ters sarkaç sisteminin sabit $\mathbf{5}^{\circ}$ açıda dengede kalması hedeflenmiştir. PID katsayılarının belirlenmesi için Ziegler-Nichols ikinci yöntemi uygulanmıştır. Yapılan analizler sonucunda kritik kazanç K_c= 72 ve salınım periyodu T_c= 0.05 olarak elde edilmiştir. Ziegler-Nichols yöntemine göre kontrol katsayıları şu şekilde hesaplanmıştır:

$$K_p = 0.6xK_c$$

$$K_d = 0.12xT_c$$

$$K_i = 0.5xT_c$$

Elde edilen bu katsayılar MATLAB/Simulink ortamında uygulanmış ve sistemin referans açı olan $\mathbf{5}^{\circ}$civarında kararlı hale gelmesi sağlanmıştır. PID kontrolör, sarkaç hareketinin referans nokta etrafında salınımını azaltmış ve kısa sürede kararlı konuma yakınsama sağlamıştır.

4. SONUÇ

- Bu çalışmada, biyomedikal uygulamalarda kullanılmak üzere küçük ölçekli, tek eklemli manyetik ters tek sarkaç mekanizmasının tasarımı, matematiksel modellenmesi ve PID kontrollü sayısal benzetimi gerçekleştirilmiştir. Geliştirilen modelin hem mekanik hem de elektromanyetik bileşenleri ayrı ayrı analiz edilerek sistemin fiziksel gerçekliğe uygunluğu doğrulanmıştır.

- Parametrik incelemeler sonucunda, sönüm katsayısı, sarım sayısı ve akım gibi değişkenlerin sistem üzerindeki etkileri değerlendirilmiştir. Sönümün azalmasıyla salınım süresinin uzadığı, sarım sayısı ve akımın artmasıyla sistemin tepki hızının yükseldiği gözlemlenmiştir. MATLAB/Simulink tabanlı model, farklı çalışma koşullarında kararlı ve beklenen tepkileri sergilemiştir. PID kontrol uygulamasıyla sistemin belirlenen referans açı etrafında dengeye yakınsaması sağlanmıştır.

- Bu model, daha ileri kontrol algoritmaları ve görev bazlı uygulamalar için güçlü bir temel oluşturmaktadır. Tüm bu çalışmalar, gelecekte biyomedikal uygulamalarda kullanılabilecek yüksek hassasiyetli ve uzaktan kontrollü manyetik manipülatör sistemlerinin geliştirilmesine katkı sağlayacaktır.

5. TEŞEKKÜR

Bu çalışmanın gerçekleştirilmesinde sundukları bilgi, teknik destek ve rehberlik imkanları için DOMEKS Makine A.Ş. Tasarım Merkezi'ne teşekkür ederiz.

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TRANSFORMATION IN LOGISTICS: AUTOMATION OF DELIVERY VERIFICATION PROCESSES THROUGH THE POD TRACKING SYSTEM

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ABSTRACT

One of the mosit important difficulties in the logistics sector is “verifying delivery processes manually”. Addition to this, document management is also another problem. Because of these problems, in this sector, digital and automatic processes are less than desired. This paper investigates one point of this situation. For this reason, first of all a tracking system is investigated. Tracking systems are important components of logistic sector. The system analyzed in this paper handles the processes in a real time concept. The system obtains some data that can be visual data (pictures and so on). This system has a special name as Proof of Delivery and an abbrevation as POD and the system was constituted in TLS Logistics Inc. TLS Logistics Inc. is a large-scale and leader logistic company in Turkey which is located in Tuzla, Istanbul. The POD system used and tested the companies’ real data so the processes of the system tracked a real process. The company currenty used another system whose name is Transportation Management System and abbrevation is TMS. POD system also developed to integrate this existing system, so by combining the powers of the two systems, it is planned to increase the company's performance and increase efficiency.

Keywords: Logistic, Proof of Delivery, Transportation Management System

1. Introduction

This section explains the need for such a study and provides a general explanation of the study's purpose to address these needs. Published studies in the literature that provide support for the study are cited to demonstrate its potential to achieve this goal. A review of the studies in the literature reveals many similarities to the present study.

As in many other sectors, ensuring smooth delivery processes in the logistics and supply chain sector is crucial. Accurate data acquisition is crucial in this process. Data can be received from many different sources, in different formats, and in different formats; the structures of the documents containing the data may not be compatible with the structures used by logistics companies. In such cases, undesirable outcomes can include complete data or document loss, corruption, processing of incorrect data, incorrect calculations in payment transactions, and errors and omissions in filing. All of these can lead to delays in the process and the supply chain. In such cases, it is necessary to first conduct data acquisition studies, then to examine system compatibility. Unfortunately, even more concerning is the fact that these processes are still largely carried out in a traditional manner in these sectors, and the rate of digitalization and automation remains very limited. In the literature, the problems that arise due to the abundance of manual processes and the scarcity of digital/automatic processes have found their place in many articles.The articles are summarized in Table 1.

As studies in the literature demonstrate, companies in the logistics sector are undertaking digital transformations to solve many problems. These problems include meeting customer expectations and all issues related to deliveries. Furthermore, because the logistics sector is a global sector, serving all sectors, it is observed that there is global competition among companies, pushing companies to be pioneers in digital transformation. According to the Digital Supply Chain Survey conducted by PwC, all digital transformation structures in the sector provide advantages across many different criteria in logistics and supply chain processes. These advantages include speed, transparency, and efficiency (Geissbauer et al., 2018). The importance of real-time data flow in the logistics sector within the framework of Industry 4.0 is well known. This is clearly evident when considering the instantaneous changes in data in the logistics sector. Zhang's (2017) study also emphasizes this point.

Table1: Literature Review

Ref	Year	Explanation
Dölek	2015	Examines the role of information technologies in logistics operations and their contribution to efficiency.
Ramos et al.	2020	Highlights general issues between the fields of logistics and supply chain management.
Freichel et al.	2020	Analyzes the challenges of supply chain visibility in logistics.
Ekanayake et al.	2024	Investigates how documentation errors in the supply chain lead to process delays.
MechSoft	2024	Addresses general information, emphasizes that digital transformation eliminates the inefficiencies of traditional processes in the logistics sector, increasing both data accuracy and process visibility.
Okumuş et al.	2024	Examines the challenges of logistics and supply chain processes.
The Select Optimus	2024	Addresses the importance of digitalization in logistics.
Aktepe	2025	Demonstrates the advantages of TMS software during digital transformation in the logistics sector.
Evren Bilgisayar	2025	States that traditional logistics methods require digital transformation and the replacement of manual systems with digital and automated processes.

This study introduces the POD Tracking System, developed by TLS Logistics to address operational challenges by digitizing document management through the collection of photo and signature data at the time of delivery. The primary goal of the study is to prevent document loss by uploading scanned delivery documents to the system, thus addressing one of the persistent problem areas in logistics. By establishing a digital bridge between drivers, operations specialists, and archiving units, the system transforms the delivery verification process into a fully traceable and auditable workflow.

2. Materials and Methods

This section describes the materials and methods used in the study. This section consists of several separate sections. The first section describes the materials used in the study. This material includes numerous elements, including the data format used, the programming language and environment used, control mechanisms, testing options, and procedures

implemented for user-friendly use. The second section of this section is entirely devoted to the methodology, focusing specifically on the modules within the system architecture that could be the output of the study. The system was designed in a modular structure, and the integration of the modules within the system was subsequently implemented.

2.1. Methodology and Technology

This part explains the materials of the study. This material includes numerous elements, including the data format used, the programming language and environment used, control mechanisms, testing options, and procedures implemented for user-friendly use.

This study was designed based on the principles of Business Process Management (BPM) methodology and structured upon a multi-tier software architecture. BPM, as defined by Gartner, employs methods to discover, model, analyze, measure, improve and optimize business strategy and processes. While it is sometimes confused with task and project management, the business process management scope is broader than these adjacent topics. Task management focuses on individual tasks whereas BPM observes the whole end-to-end process. Project management refers to a one-time scope of work while BPM focuses specifically on processes that are repeatable. Through continuous process reengineering, organizations can streamline their overall workflows, leading to increased efficiencies and cost-savings. This concept isn't new; six sigma and lean principles are examples of BPM methodologies. By incorporating advanced analytics, activity monitoring, and decision management capabilities, business process management suites are able to coordinate people, systems, and information and material to achieve business outcomes. As a result, they have been particularly helpful in accelerating digital transformation strategies.

Koç and Akın (2025) particularly conceptualized this framework within the context of digital archiving and data integrity in delivery verification processes. The BPM approach aims to model, analyze, monitor, and continuously improve organizational processes in a systematic manner, thereby enhancing operational efficiency.

The system architecture developed for this study consists of three main components: a presentation layer, a business logic layer, and a data access layer. This layered structure improves the system's maintainability, modularity, and reusability, providing a sustainable and long-term solution. Performance and scalability were prioritized during the development process, and a .NET Framework-based infrastructure was selected.

This decision was made due to the framework's platform-independent development capabilities and high compatibility with existing enterprise systems. Microsoft SQL Server was used as the database management system for data management and storage. Microsoft SQL Server is a relational database management system (RDBMS). Applications and tools connect to a SQL Server instance or database, and communicate using Transact-SQL (T-SQL). SQL Server's robust data integrity checks, security mechanisms, and transactional performance ensured the reliable processing of high-volume data streams. User testing, scenario-based validation, and role-based authorization mechanisms were implemented throughout the system development phase.

User tests were conducted to evaluate system functionality and user experience under various scenarios, while scenario-based validations simulated real-world operational processes to measure the system's fault tolerance. Furthermore, role-based access control (RBAC) mechanisms were defined to strengthen system security, ensuring each user only accessed authorized modules. This structure effectively protected data confidentiality, integrity, and traceability.

Consequently, the developed system offers an integrated solution for digitizing corporate processes, both technically and methodologically. It establishes a sustainable infrastructure that enhances process automation, data accuracy, and operational traceability.

2.2. System Components and Integration

This part is entirely devoted to the methodology, focusing specifically on the modules within the system architecture that could be the output of the study. The system was designed in a modular structure, and the integration of the modules within the system was subsequently implemented.

The POD Tracking System consists of four core components: the Web-Based Management Panel, Mobile Driver Application, TMS Integration Layer, and Power BI (Business Intelligence) Reporting Component.These components are summarized in the table.

Table 2: POD Tracking System Components

Name	Explanation
Web-Based Management Panel	Primary interface used by operations specialists and archiving units to manage delivery data, monitor ongoing processes, and access reporting dashboards.
Mobile Driver Application	Used by field drivers to take photos during deliveries, collect digital signatures, and scan and upload delivery documents, enabling real-time data transmission.
TMS Integration Layer	Manages workflow by exchanging data with the existing Cyber Transportation Management System (TMS) through real-time API integrations. Integration reduces administrative costs, automates booking and documentation processes, and thus increases operational efficiency.
Power BI Reporting Component	Provides real-time Key Performance Indicators and operational efficiency analytics for management. The data-driven insights generated by this component help logistics managers make strategic, evidence-based decisions.

3. Results

The main findings obtained from the study are summarized as follows in the table.

Table 3:The Main Findings of POD System

Findings	Explanation
Digital Archiving Potential and Document Loss Prevention	The mobile app's ability to instantly and dynamically collect visual data (signatures, photos, etc.) at the point of delivery reduces the amount of manual documentation in workflows.
Operational Speedup Expectation	Real-time transmission of delivery data to the TMS accelerates both the confirmation of deliveries and the initiation of subsequent financial processes. As a result, an operational efficiency increase of 30% to 40% is expected. This finding aligns with the general academic view that digital technologies increase the flexibility and responsiveness of logistics and supply chain networks.
Real-Time Management and Visibility:	Dynamic reports generated through Power BI allow managers to monitor key performance indicators in real time, significantly accelerating operational decision-making. Real-time monitoring and visibility are among the most valuable benefits offered by modern TMS software. This feature provides management with continuous visibility into delivery confirmations, allowing them to proactively identify process bottlenecks and performance anomalies.

Visual representations of the system are presented below:

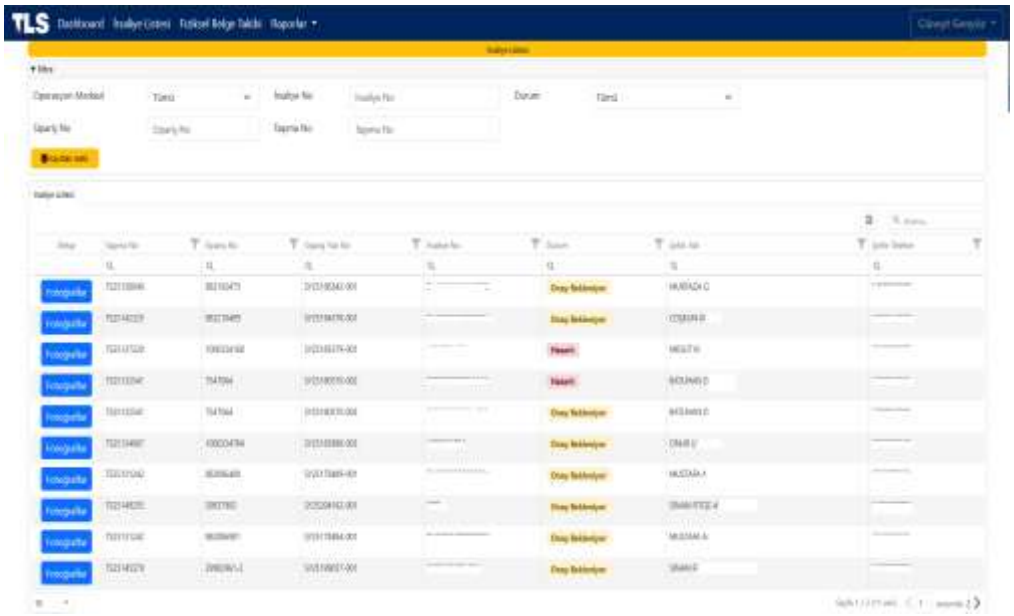

Figure 1: TLS POD Tracking System – 1

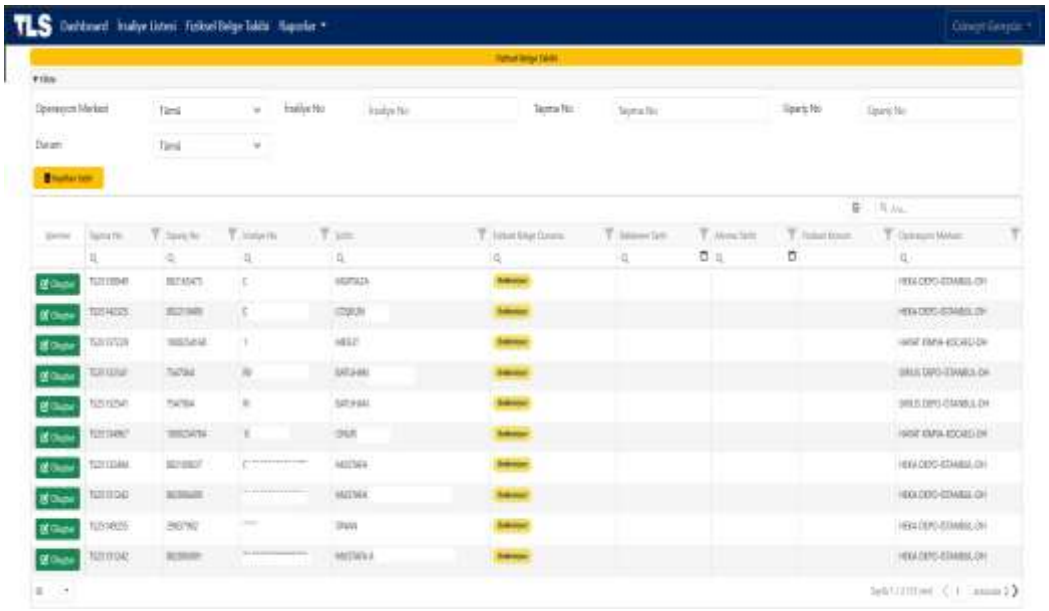

Figure 2: TLS POD Tracking System – 2

Following the initial deployment of the system, implementation outcomes and early operational data indicate strong evidence that the project will successfully address the initially targeted operational problems. These early results confirm that the system is capable of producing measurable improvements in accuracy, traceability, and speed across delivery verification processes.

4. Discussions and Conclusions

This study presents the design, technological infrastructure, and implementation results of a POD Tracking System developed to digitize delivery verification and document management processes in the logistics sector. Key findings demonstrate that digital transformation provides significant gains not only in operational speed and accuracy, but also in corporate information management and process traceability. The systematic elimination of chronic problems such as document loss, data inconsistencies, and approval delays in manual processes was made possible through digital archiving and real-time data synchronization. The results demonstrate an approximately 30-40% operational speedup in delivery verification processes and a significant reduction in document loss incidents. These findings are consistent with literature emphasizing that digitalization increases supply chain visibility and process efficiency. Furthermore, thanks to the system's multi-layered architecture and real-time integration with the TMS, information flows are integrated and fully traceable. Consequently, communication between field operations and central management units is streamlined, and processes are end-to-end traceable and auditable. The Power BI-based reporting component provides analytical visibility that strengthens a data-driven management culture in decision-making. However, some limitations were observed during implementation. First, differences in mobile device infrastructure and fluctuating internet connection quality in the field led to periodic inconsistencies in data transfer speeds. Furthermore, user adaptation to the digital system took time, requiring additional training and user support in the early stages of deployment. These challenges demonstrate that the human factor remains a decisive factor in digital transformation projects. Future work related to this study and the topic can be summarized as follows in the table.

Table 4: Future Work

Name	Explanation
Artificial Intelligence-Based Image Processing and Document Verification	Integration of Artificial Intelligence-based image processing systems is planned to automate the manual document verification and data entry tasks currently performed by warehouse personnel. The system will automatically detect signatures, stamps, and key verification elements on uploaded invoices and delivery notes to verify their legal accuracy. Shipment data from shipping documents will be directly transferred to TMS and ERP systems, eliminating the need for manual data entry. This enhancement is expected to increase data accuracy and reduce personnel-related operational costs.
Financial Process Integrations	The system scope should be expanded to include integration with financial processes such as invoicing, payment tracking, and cost analysis. The financial integration capabilities of TMS platforms are critical for improving cost control and strategic decision-making in logistics operations.
Customer Portal Module	The addition of a customer-centric portal that allows customers to track orders and view digital signatures or documents will enrich the customer experience and improve service quality.

In conclusion, the POD Tracking System represents a significant milestone in TLS Logistics' digital transformation journey. This study provides an integrated digital infrastructure that reduces manual workload, increases process transparency, and supports operational excellence in the logistics sector. In this respect, it serves as a model of digitalization that holds value for both industry applications and academic research.

Abbrevation List:

BI : Business Intelligence

BPM : Business Process Management

NET: Network

POD : Proof of Delivery

RBAC: Role-Based Access Control

RDBMS : Relational Database Management System

SQL : Structured Query Language

TMS : Transportation Management System

T-SQL: Transact-SQL

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A PYTHON BASED FRAMEWORK FOR KINEMATIC AND DYNAMIC ANALYSIS AND SIMULATION OF INDUSTRIAL ROBOTIC ARMS

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ABSTRACT

Industrial robotic arms not only provide precision, efficiency, and flexibility in manufacturing systems but also play a critical role in modeling kinematic and dynamic analyses within academic research. The study of robots with multiple degrees of freedom requires complex mathematical computations, posing significant challenges in both educational and research contexts. In this study, interactive simulation software was developed to enable such analyses to be performed in a more accessible, simplified, and modellable manner. In the proposed system, all mathematical computations and three-dimensional visualization processes were carried out using the Python programming language. Advanced algorithms such as the Denavit–Hartenberg matrix method, the inverse Jacobian technique, the Euler–Lagrange formulation, the Newton–Euler method, and the Recursive Newton–Euler Algorithm (RNEA) were employed for the mathematical operations. The application includes forward and inverse kinematics, forward and inverse dynamics, a Python-based simulation environment for the Kinematics, Dynamics, and Trajectory Planning of Industrial Robot Arms, as well as trajectory planning and workspace simulations. The accuracy, speed, and usability performance of the software were evaluated in detail. The results demonstrate that the system produces reliable solutions across different joint configurations and accurately computes end-effector positions. Therefore, this study provides a low-cost, interactive, and extensible simulation platform suitable for both educational and research purposes, offering a significant contribution to the academic field.

Keywords: Robotic Arms, Robotic Kinematics, Robotic Dynamics, Simulation Software, Mathematical Analysis, Trajectory, Workspace

1. INTRODUCTION

Industrial robots are among the fundamental components of modern manufacturing and automation systems, playing a critical role in achieving high precision, repeatability, and increased production speed. Multi-degree-of-freedom robotic arms are widely used across various industries such as automotive, aerospace, electronics, and healthcare. The effective utilization of these systems depends on the accurate execution of kinematic and dynamic analyses. Such analyses enable the mathematical modeling of a robot's motion capabilities, ensure that the end effector reliably reaches designated task points, and provide the precision required in industrial processes. Consequently, the importance of software and simulation tools developed in the field of robotics has been steadily increasing.

Studies on the kinematic and dynamic analyses of industrial robotic arms particularly emphasize the significance of software-based simulation tools. Among the most widely used methods in the literature are Denavit–Hartenberg (DH) transformations, homogeneous transformation matrices, and recursive algorithms [1]. While these methods offer reliable solutions for forward and inverse kinematic computations, numerical approaches that provide general solutions are also frequently preferred, especially when compared to analytical methods that are valid only for specific robot configurations.

A review of studies on dynamic modeling reveals that this topic has been addressed in the literature with a narrower scope compared to kinematics. A limited number of works have examined forward and inverse dynamic models using specialized tools such as the ARAT Toolbox or by implementing multibody dynamic algorithms in Python environments [2]. However, most research has overlooked dynamic modeling and has focused predominantly on kinematic computations and trajectory planning. Various approaches to trajectory planning have been reported. Some studies employing sampling-based algorithms (RRT, PRM, EST) have achieved task completion rates of up to 27.9% and reduced task durations to under 20 minutes [3]. Other works have utilized hybrid optimization methods (PSO, SSO, GWO, etc.) to improve path length, jerk, and acceleration values [4]. Artificial neural networks [5] and computer-vision–based artificial intelligence techniques [6] have also been applied in inverse kinematics and object recognition processes. Research findings indicate that MATLAB/Simulink-based tools dominate the literature, although Python-supported 3D interfaces have recently begun to gain prominence [7]. The open-source libraries offered by Python provide flexible solutions for both kinematic/dynamic computations and three-dimensional visualization, enabling the development of user-friendly interfaces. Reported performance metrics show that one study achieved an accuracy of 0.2 mm, while another reported error values ranging between 0 and 22 mm [8]. The Denavit–Hartenberg (DH) method is among the most widely used techniques in forward kinematic analysis (Denavit & Hartenberg, 1955). Through homogeneous transformation matrices defined via coordinate frames assigned to each joint, the DH method expresses the geometric relationship between adjacent joints. The transformation matrix representing the relationship between two consecutive joints is denoted as ${}^{i-1}_{i}T$, where "i" indicates the link number.

$$ {}^{i-1}_{i}T = \begin{bmatrix} {}^{i-1}_{i}R & D \\ 0\ 0\ 0 & 1 \end{bmatrix} \tag{1} $$

Here ${}^{i-1}_{i}R$, represents the rotational relationship between two consecutive joints, while D denotes the translational displacement vector. By multiplying the resulting transformation matrices, the position of the end effector with respect to the base coordinate frame is obtained:

$$ {}^{0}_{5}T = {}^{0}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T\,{}^{3}_{4}T\,{}^{4}_{5}T\,{}^{5}_{e}T \tag{2} $$

Here, "e" denotes the end effector, and each ${}_{i}^{i-1}T$ m matrix defines the transformation relationship between consecutive joints. Thus, the homogeneous transformation matrix of the end effector with respect to the base is obtained, and from this matrix both the position components p_x, p_y, p_z and the orientation components n, s, α can be extracted. The first column of the matrix represents the normal vector n, the second column represents the sliding vector s, and the third column represents the approach vector α. Inverse kinematics is the process of determining the joint variables when the position and orientation of the end effector are given. Unlike forward kinematics, a solution may not always exist. The forward kinematics of a six-degree-of-freedom robot can be expressed as follows: [9] [10]

$$ {}_{6}^{0}T = {}_{1}^{0}T\,{}_{2}^{1}T\,{}_{3}^{2}T\,{}_{4}^{3}T\,{}_{5}^{4}T\,{}_{6}^{5}T \tag{3} $$

By multiplying both sides of the equation by $[{}_{i}^{i-1}T]^{-1}$ the expression is rearranged to obtain the required relationships. The remaining equations can be derived in a similar manner.

$$ [{}_{1}^{0}T]^{-1}\,{}_{6}^{0}T = {}_{2}^{1}T\,{}_{3}^{2}T\,{}_{4}^{3}T\,{}_{5}^{4}T\,{}_{6}^{5}T \tag{4} $$

These equations yield the solutions to the inverse kinematics problem by equating the matrix elements on both sides of the expression. To accurately compute the forces and moments encountered during the robot's motion, a dynamic analysis is required. Dynamic analysis not only considers the kinematic solutions but also accounts for the inertia, mass, and gravitational effects acting on the robot. One of the most commonly used methods for this purpose is the Lagrange formulation. In the Lagrangian approach, the system's kinetic energy

$K(q, q')$ and potential energy $P(q)$ are first defined. The Lagrange function is then expressed as follows [11]:

$$ L(q, q') = K(q, q') - P(q) \tag{5} $$

The equations of motion are derived using the Lagrange equations.

$$ \frac{d\left(\frac{\partial L(q,q')}{\partial q'}\right)}{dt} - \frac{\partial L(q,q')}{\partial q} = \tau \tag{6} $$

When these expressions are rearranged, the dynamic model of the robotic arm can be written in the following form:

$$ M(q, q'') + C(q, q')q' + g(q) = \tau \tag{7} $$

Here:

- $q \in R^n$ is the vector of joint coordinates,
- $M(q, q') \in R^{n \times n}$, is the inertia matrix,
- $C(q, q')q' \in R^n$ is the vector of Coriolis and centrifugal forces,
- $g(q) \in R^n$ is the vector of gravitational forces,
- $\tau \in R^n$ represents the vector of joint torques.

The Coriolis and centrifugal effects are defined as follows:

$$ C(q, q')q' = M'(q, q') - \frac{1}{2}\frac{\partial\left(q'^{T} M(q) q'\right)}{\partial q} \tag{8} $$

The gravitational effect is derived from the potential energy function.

$$g(q) = \frac{\partial(P(q)}{\partial q} \tag{9}$$

The dynamic model obtained from the analysis not only facilitates the derivation of the robot's equations of motion but also provides a critical foundation for control design, trajectory planning, and the development of optimization algorithms. Although some studies in the literature have performed dynamic analyses using tools such as MATLAB/Simulink or the ARAT Toolbox, Python-based solutions have become increasingly widespread [7] [2]. This study aims to offer both an academic and practical solution for the kinematic and dynamic analyses of industrial robotic arms. The developed software serves as a platform that helps students in educational institutions better understand complex robotic computations, while also supporting simulation-based testing processes in applications that enable researchers to develop new algorithms.

METHODOLOGY

1.1. Model Preparation

In the developed software, the three-dimensional CAD models of the robotic arms were initially designed in SolidWorks, and the axes and origins were arranged according to the widely used right-hand rule in the literature. These models were then exported in the commonly used STL (.stl) format (Figure 1). Subsequently, the models were imported into the Python environment through Unified Robot Description Format (URDF) files, which define the kinematic chain of the robot. Through this process, the coordinate system of each joint was established, and the corresponding homogeneous transformation relationships were made available for use within the software (Figures 2–3). The system's user interface was developed using the PyQt5 framework.

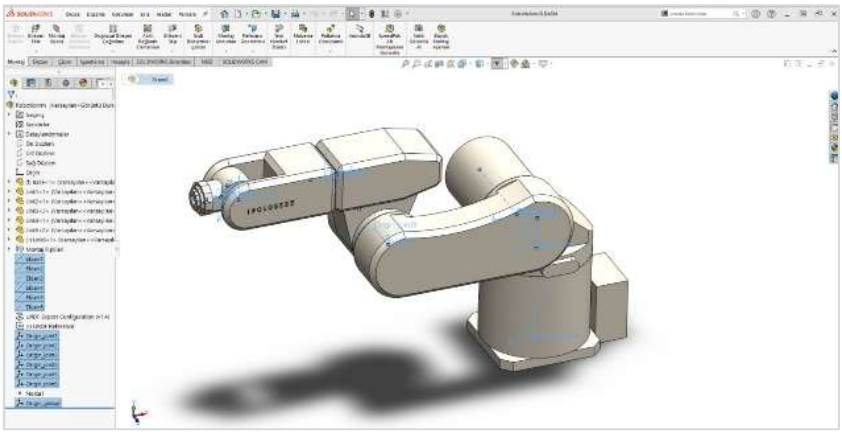

Figure 1 3D Model of Robot

```
self.robot = URDF.load("./assets/RoboticArm.SLDASM/urdf/RoboticArm.SLDASM.urdf")
self.visualizer = RobotVisualizer(self.robot)
```

Figure 2 URDF File Upload



Figure 3 Creation of the Scene

1.2. Forward Kinematics Analysis

The system is built upon the integration of the mathematical framework and dynamic analyses. For forward kinematic computations, homogeneous transformation matrices were defined using the Denavit–Hartenberg (DH) parameters, and the position and orientation of the end effector with respect to the base coordinate frame were obtained. Figure 4 illustrates the six-degree-of-freedom joint structure of the KUKA KR5 R650 industrial robot, in which the rotation axes of each joint are shown with colored coordinate frames. This representation clearly defines the kinematic chain from the base coordinate system to the end effector and provides the fundamental infrastructure for constructing the forward kinematic model.

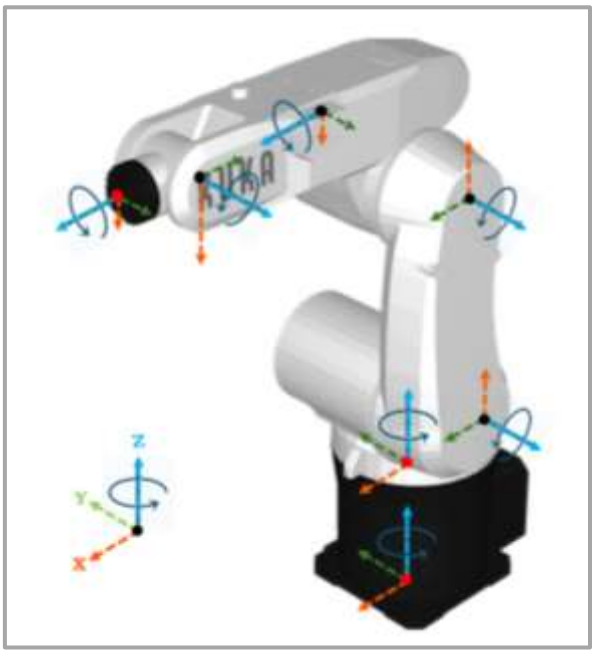

Figure 4 Joint Axes of the KUKA KR5 R650 Robot

Figure 5 shows the link lengths and joint limits used in constructing the forward kinematic model of the KUKA KR5 R650 robot. The robot has six degrees of freedom, and the rotational

angles defined for each joint are expressed as (Q1…Q6). The angle limits provided on the right indicate the mechanical constraints of the robot and play a critical role in determining its workspace. This kinematic scheme forms the basis for defining the Denavit–Hartenberg parameters and deriving the forward kinematic equations.

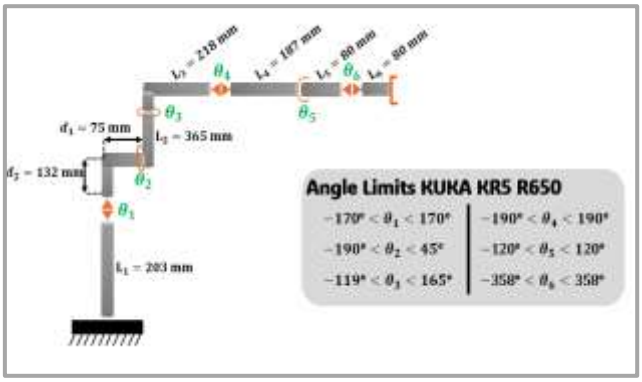

Figure 5 Kinematic Structure and Joint Limits of the KUKA KR5 R650 Robot

In this section, the forward kinematic model of the manipulator is defined using the Denavit–Hartenberg (D–H) parameters. Each homogeneous transformation matrix represents the position and orientation relationship between successive coordinate frames. The multiplication of all transformation matrices yields the position and orientation of the end effector with respect to the base coordinate frame.

$$T_{01} = \begin{bmatrix} cos\,\theta^1 & 0 & sin\,\theta^1 & 75\,cos\,\theta^1 \\ sin\,\theta^1 & 0 & -cos\,\theta^1 & 75\,sin\,\theta^1 \\ 0 & 1 & 0 & 135 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{10}$$

$$T_{12} = \begin{bmatrix} cos\,\theta^2 & -sin\,\theta^2 & 0 & 283\,cos\,\theta^2 \\ sin\,\theta^2 & cos\,\theta^2 & 0 & 283\,sin\,\theta^2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{11}$$

$$T_{23} = \begin{bmatrix} cos\,\theta^3 & 0 & sin\,\theta^3 & 0 \\ sin\,\theta^3 & 0 & -cos\,\theta^3 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{12}$$

$$T_{34} = \begin{bmatrix} cos\,\theta^4 & 0 & -sin\,\theta^4 & 0 \\ sin\,\theta^4 & 0 & cos\,\theta^4 & 0 \\ 0 & -1 & 0 & 295 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{13}$$

$$T_{45} = \begin{bmatrix} cos\,\theta^5 & 0 & sin\,\theta^5 & 0 \\ sin\,\theta^5 & 0 & -cos\,\theta^5 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{14}$$

$$T_{56} = \begin{bmatrix} cos\,\theta^6 & -sin\,\theta^6 & 0 & 0 \\ sin\,\theta^6 & cos\,\theta^6 & 0 & 0 \\ 0 & 0 & 1 & 80 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{15}$$

The general transformation matrix of the end effector is obtained by multiplying all consecutive transformation matrices.

$$T = T^{01} \cdot T^{12} \cdot T^{23} \cdot T^{34} \cdot T^{45} \cdot T^{56} \quad (16)$$

The Cartesian position (X, Y, Z) of the end effector is computed from the last column of the resulting transformation matrix.

$$X = cos(\theta_1)\,(283cos(\theta_2) + 1200sin(\theta_2) + 1545cos(\theta_2+\theta_3) + 145sin(\theta_2+\theta_3) + 158cos(\theta_2+\theta_3+\theta_4)) \quad (17)$$

$$Y = sin(\theta_1)\,(283cos(\theta_2) + 1200sin(\theta_2) + 1545cos(\theta_2+\theta_3) + 145sin(\theta_2+\theta_3) + 158cos(\theta_2+\theta_3+\theta_4)) \quad (18)$$

$$Z = 135 + 1200cos(\theta_2) - 283sin(\theta_2) + 145cos(\theta_2+\theta_3) - 1545sin(\theta_2+\theta_3) + 158sin(\theta_2+\theta_3+\theta_4) \quad (19)$$

The algorithm used in forward kinematic calculations is shown in Figure 6. This structure enables the construction of transformation matrices for each joint and the computation of inter-joint relationships through sequential multiplications. Through the resulting transformation matrices, the position and orientation of the manipulator with respect to the base coordinate frame can be determined for any joint configuration. The determination of the end effector's Cartesian coordinates is illustrated in Figure 7. At this stage, the X, Y, and Z components of the end effector are obtained using the last column of the transformation matrix, thereby computing the manipulator's position within its workspace. This method has been validated through MATLAB/NumPy-based numerical computations for different joint angles.

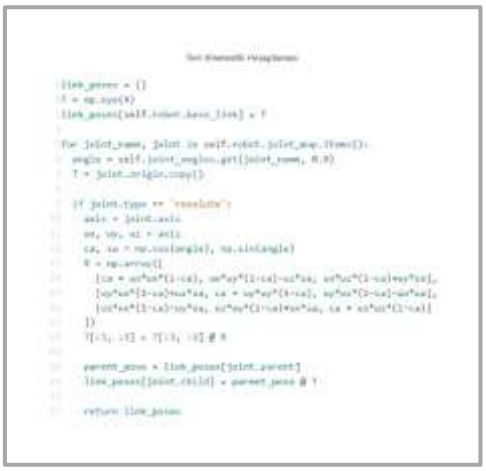

Figure 6 Forward Kinematic Calculations



Figure 7 Computation of the End Effector Position

1.3. Inverse Kinematics Analysis

Inverse kinematic solutions were obtained using closed-form approaches when analytical methods were applicable, while numerical optimization techniques were employed in more general cases. In the dynamic analysis stage, the Newton–Euler formulation and the Recursive Newton–Euler Algorithm (RNEA) were used, enabling the systematic computation of the forces and torques acting on the joints.

1.4. Workspace Representation

In this study, a numerical sampling–based method was used to compute the workspace. First, the minimum and maximum allowable joint angle ranges for each joint of the robot arm were defined. Then, samples were selected from these ranges either randomly or at regular intervals. For each selected joint combination, the forward kinematic equations were solved to compute the position of the end effector with respect to the base coordinate frame [Figure 8]. The obtained positions were recorded and visualized as a three-dimensional point cloud [Figure 9]. In this way, the workspace was visually represented by the set of all points that the robot can reach.

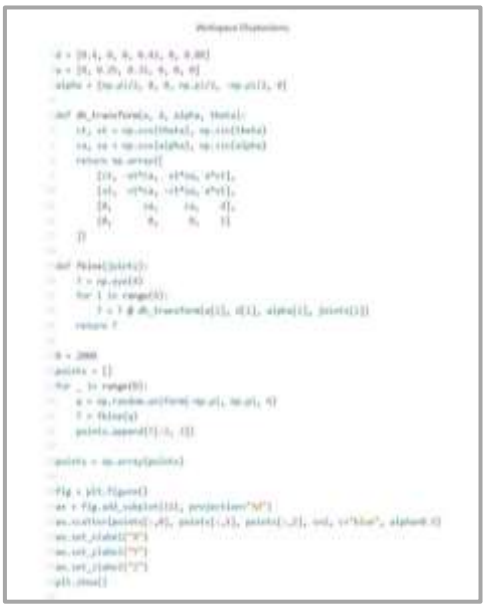

Figure 8 Extraction of the Robot Workspace

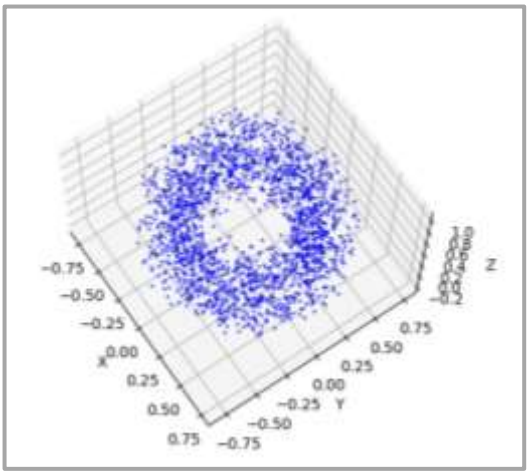

Figure 9 Robot Workspace

1.5. Dynamic Analysis

The software architecture was built on the Python programming language and developed using open-source libraries. NumPy and SciPy were utilized for mathematical computations, while the user interface was designed with PyQt5. Through the interface, each component can be controlled, and the position and orientation of the end effector can be computed and visualized in real time. For the integration of three-dimensional models, URDF files were processed using the yourdfpy library, and the robot's 3D model was visually rendered with the support of Open3D and PyQtGraph. This approach shows strong parallels with Python-based 3D interface development studies reported in the literature [7] [6].

2. RESULTS

Using the simulation software developed in this study, forward and inverse kinematics, dynamic analysis, trajectory planning, and workspace simulations were performed. Figure 10 shows the developed user interface. On the interface, the joint angle limits defined for each joint can be adjusted using slider bars, allowing the user to interactively test different configurations of the manipulator. The obtained joint angles are applied to the forward kinematic equations, enabling the real-time computation and display of the end effector's position in the X, Y, and Z coordinates. This approach not only supports the validation of the model but also allows the user to visualize the manipulator's workspace.

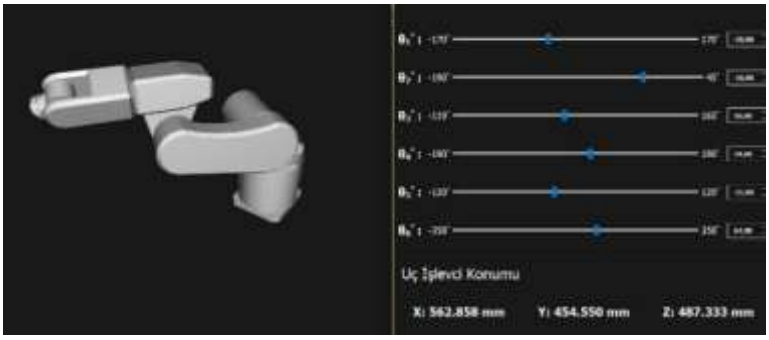

Figure 10 Forward Kinematic Interface

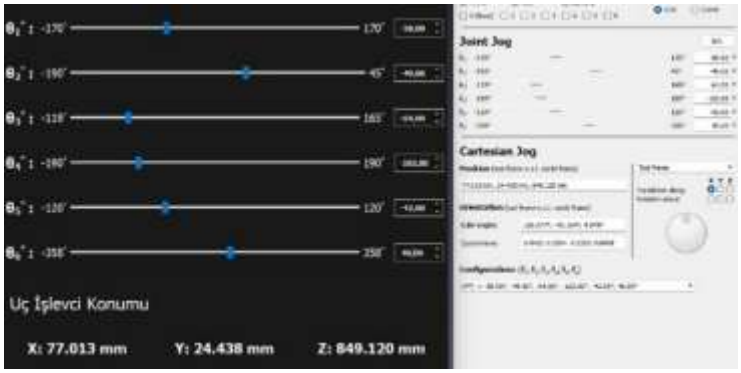

Figure 11 Comparison of the Developed Software with the RokiSim Program

First, the forward kinematic calculations were tested, and the position and orientation of the end effector with respect to the base coordinate frame were obtained for the given joint angles. The obtained values were compared with the theoretical results calculated using the Denavit–Hartenberg parameters and the results obtained from the RokiSim program, and they were determined to be error-free (Figure 11).

In the inverse kinematic analysis, joint angles were computed using numerical methods for different end effector positions and orientations, and the results were validated through forward kinematics. The tests showed that when only the position was targeted, the end effector position error was at the micrometer level. When both position and orientation were targeted, the average error was approximately ±5 mm, with 95% of the cases remaining within the ±2–3 mm range. The orientation error was found to be 0.16° on average, reaching a maximum of 5°. These results demonstrate that the developed software provides high accuracy and reliability in inverse kinematic solutions (Figures 11–13).

```
=== IK Test Sonuçları ===
Pozisyon testi (yalnız p):  başarı=100.0%  N=60
  Konum hatası (m): {'mean': 8.681904308163162e-07, 'median': 2.3332381216231514e-07, 'max': 1.1823649533084457e-05, 'p95': 2.950206111733058e-06}
Poz+Yönelim testi (p+R):  başarı=100.0%  N=60
  Konum hatası (m): {'mean': 0.004776724108433021, 'median': 8.480861915377522e-10, 'max': 0.15881226537592097, 'p95': 0.002438598572950534}
  Yönelim hatası (rad): {'mean': 0.002818948711878146 6, 'median': 0.0, 'max': 0.08800718801945018, 'p95': 0.0015679352472903409}
```

Figure 12 Inverse Kinematic Results

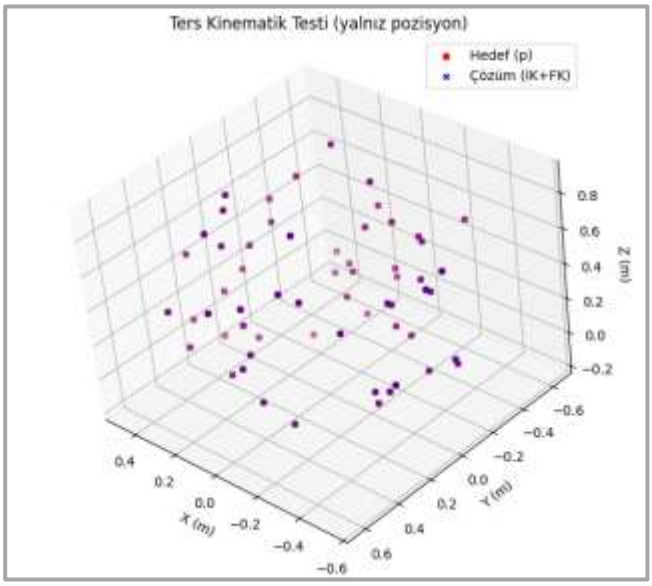

Figure 13 Results Obtained for Inverse Kinematics

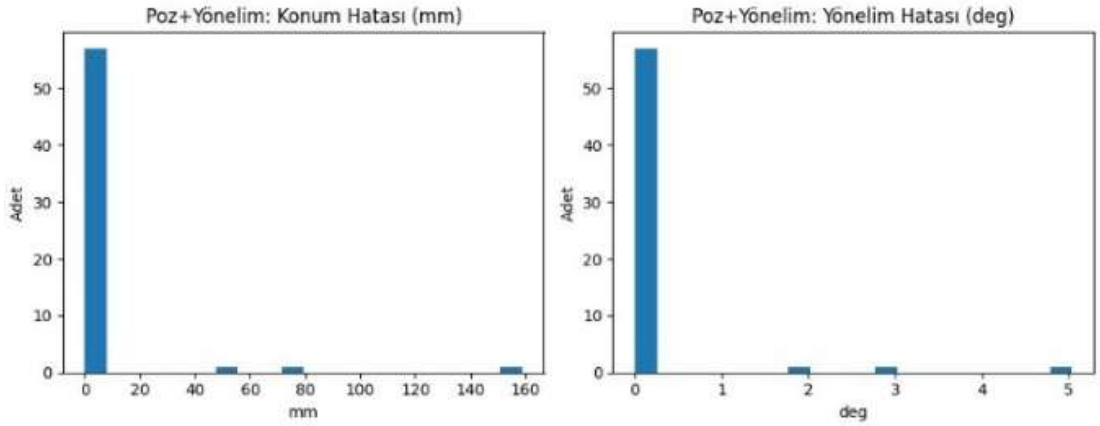

Figure 14 Results Obtained for Inverse Kinematics

For dynamic validation, time-dependent joint trajectories were generated on a two-degree-of-freedom planar test system, and the torque components were decomposed using the equations

derived from the Lagrange and RNEA formulations. The total torque was plotted together with the inertia term $M(q,q'')$, the Coriolis and centrifugal term $C(q,q')q'$ and the gravity term $g(q)$[Figure 15]. Energy consistency and the numerical consistency of the Lagrange formulation were demonstrated [Figure 16]. Finally, a 0.5 kg load was added to the end effector, and the corresponding increase in the torque curves was illustrated (Figure 17). The obtained results confirm that the model is physically consistent and exhibits the expected behavior under dynamic loads.

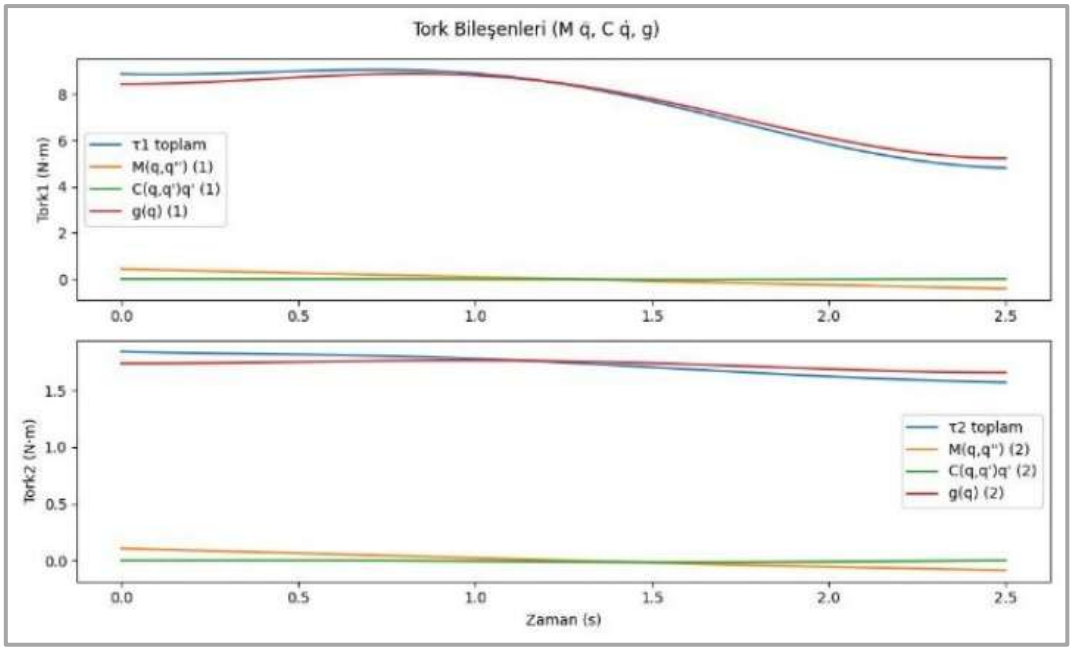

Figure 15 Torque Components

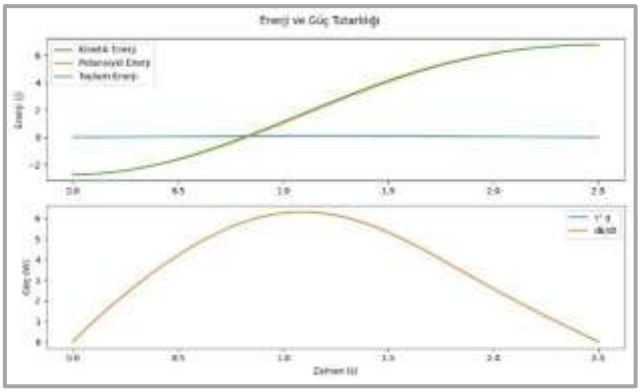

Figure 16 Total Energy Test and Lagrange Formulation

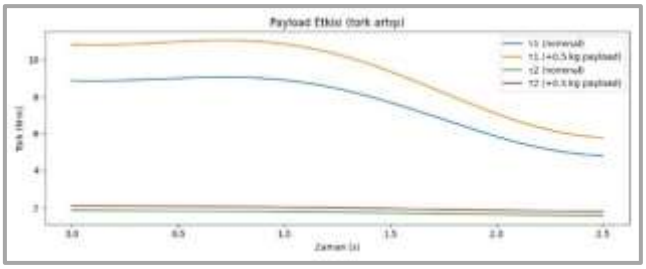

Figure 17 Comparison of Torques with Load

3. CONCLUSIONS

In this study, a system was developed that performs the forward and inverse kinematics, dynamic analysis, and trajectory planning of industrial robotic arms within an integrated software platform. Built using Python-based open-source libraries, the software not only solves theoretical equations but also provides users with an interactive simulation environment through its three-dimensional visualization capability. In forward kinematic analysis, the position and orientation of the end effector were calculated with high accuracy, while in inverse kinematic analysis, the target points were reached with an average error on the millimeter scale. In the dynamic analyses, joint torques were decomposed using the Recursive Newton–Euler Algorithm, and the physical consistency of the system was validated through energy and power relationships. The workspace simulations visually revealed the robot's reachable volume. The obtained findings demonstrate that the developed software offers a low-cost and flexible solution suitable for educational and research purposes. In this respect, the study constitutes an academic tool that serves as an alternative to commercial robot simulation software. Future work will expand the platform's scope by integrating more complex optimization-based trajectory planning methods, control algorithms, and compatibility with different robotic arms.

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TÜRKİYE'NİN SİVAS İLİNDE ŞEKER PANCARININ ÖNEMİ VE BİTKİ KORUMA SORUNLARI

ASSESSMENT OF SUGAR BEET SIGNIFICANCE AND PLANT PROTECTION CHALLENGES IN SIVAS PROVINCE

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ÖZET

Bu derleme, Sivas ilinde şeker pancarı üretiminin agroekonomik önemi ve bitki koruma sorunlarını entegre mücadele yaklaşımı çerçevesinde değerlendirilmek amacıyla hazırlanmıştır. Şeker pancarı (*Beta vulgaris* L.), Amaranthaceae familyasına ait, iki yıllık, yazlık bir endüstri bitkisi olup, Türkiye'de özellikle Orta ve Doğu Anadolu'nun başlıca endüstriyel tarla bitkileri arasında yer almaktadır. Makalede, şeker pancarının Türkiye şeker üretimindeki payı, ekim alanı, verim düzeyi ve sözleşmeli üretim yapısı özetlenmekte; Sivas'ın karasal iklimi ve ekolojik koşulları altında ürünün tarımsal önemi vurgulanmaktadır. Sivas ilinde şeker pancarı verimini sınırlayan biyotik ve abiyotik etmenler içinde fungal hastalıklar ön plandadır. Özellikle Cercospora yaprak lekesi, Rhizomania (kök sakallanması) ve Rhizoctonia kaynaklı taç-kök çürüklüğü hastalıkları bölgede yaygın olarak görülmekte ve önemli düzeyde verim kayıplarına neden olmaktadır. Buna ek olarak, külleme, pas hastalıkları ve Fusarium spp.'nin oluşturduğu kök çürüklükleri, bazı üretim yıllarında ve belirli alanlarda önemli boyuta ulaşabilmektedir. Hastalık ve zararlılarla mücadele için, etkin bir hastalık yönetimi; dayanıklı çeşitlerin tercih edilmesi, sağlıklı ve sertifikalı tohum kullanımı, uygun kültürel önlemler, erken tahmin–uyarı sistemlerine dayalı fungusit uygulamalarının birlikte planlanmasını gerektirmektedir. Fungal hastalıkların yanı sıra yabancı otlar ve nematodlar da Sivas koşullarında şeker pancarı verim ve kalitesini sınırlayan önemli biyotik etmenlerdendir. Pancar–tahıl ekim rotasyonu, hastalık ve yabancı ot döngülerinin kırılmasına katkı sağlamakta, buğday ve arpa ekimlerinde verim artışı sağlamaktadır. Şeker pancarında biyotik etmenlere bağlı toplam ürün kayıplarının %45,2'ye ulaşabildiği; bunun %16,5'inin zararlılardan, %16,5'inin hastalıklardan ve %12,2'sinin yabancı otlardan kaynaklandığı bildirilmektedir. Bu derleme, mevcut bilgi birikimini Sivas ili özelinde sunarak entegre bitki koruma stratejilerinin gerekliliğini ortaya koymayı ve geleceğe yönelik araştırma boşluklarını tanımlamayı amaçlamaktadır.

Anahtar kelimeler: Şeker pancarı, Sivas, fungal hastalıklar, yabancı ot ve zararlılar, entegre mücadele

Giriş

Şeker pancarı (*Beta vulgaris* L.), Amaranthaceae familyasına ait, iki yıllık, yazlık bir endüstri bitkisidir. Dünyada şeker üretiminde şeker kamışından sonra en fazla yetiştirilen tür olup, yıllık şeker üretiminin yaklaşık %30'unu karşılamaktadır. Şeker pancarı, Türkiye'de özellikle Orta ve Doğu Anadolu'nun önemli endüstriyel tarla bitkileri arasında yer almakta; Sivas gibi belirgin karasal iklime sahip, yüksek rakımlı illerde sulu tarımın temelini oluşturmaktadır (Kandil ve ark., 2020). Sivas ilinde pancar üretimi, sadece şeker sanayisine hammadde sağlamanın ötesinde, başta küspe ve melas olmak üzere yem ve gıda sanayinde kullanılan önemli bir hammadde kaynağıdır (Şiray, 1990; Anonim, 2007). Türkiye'de şeker pancarı üretimi 2024 yılında 23,0 milyon ton olarak gerçekleşmiştir. 2023 yılında ise şeker pancarı ekim alanı 3.555.950 da, üretim 23,5 milyon ton ve ortalama verim 6.609 kg/da olarak bildirilmiştir (TÜİK, 2025). Sivas'ın agroekolojik koşulları değerlendirildiğinde, üreticilerin vegetasyon süresi boyunca genellikle 5–10 sulama yapması gerekmektedir. Sulama zamanlamasının doğru planlanması ve su verimliliğinin artırılması, hem verim ve kalite parametrelerini iyileştirmekte hem de yerüstü ve yeraltı kaynaklarının etkin kullanımına katkı sağlamaktadır. Şeker pancarı; Akıncılar, Altınyayla, Gemerek, Kangal, Merkez, Suşehri, Şarkışla, Ulaş ve Yıldızeli ilçelerinde düzenli olarak yetiştirilmektedir. Bu geniş dağılım, ilin agroekolojik uygunluğunu ve sulama kapasitesini yansıtmaktadır. Ürün, sözleşmeli üretim modeliyle ve çoğunlukla il dışındaki fabrikalara Erzincan, Kayseri, Tokat/Turhal, Malatya illerinde çoklu tedarik ilişkileri üzerinden pazarlanır. Sulama yönetimi ve hasat konusunda, vejetatif büyüme ve şeker birikimi dönemlerinde hassas sulama zamanlaması verim ve polarizasyonu artırır. Sonbaharda bitki hasat olgunluğuna ulaşıldığında söküm yapılmalı; toprak bulaşıklığı ve tepe kesim kayıpları minimize edilerek polar kalitesi korunmalıdır.

Sivas ilinde şeker pancarı verimini etkileyen biyotik ve abiyotik faktörlerin başında fungal hastalıklar yer almaktadır. Özellikle bölgede Cercospora yaprak lekesi, Rhizomania (kök sakallanması) ve Rhizoctonia kaynaklı taç/kök çürüklüğü hastalıkları sıklıkla görülmekte ve önemli düzeyde verim kayıplarına yol açmaktadır. Ayrıca, külleme, pas hastalıkları ve *Fusarium* spp. tarafından oluşturulan kök çürüklükleri, belirli bölgelerde veya bazı üretim sezonlarında önem kazanabilmektedir. Etkin bir hastalık kontrol programı; dayanıklı çeşitlerin kullanılması, sağlıklı ve sertifikalı tohum materyali, uygun kültürel önlemler, erken tahmin–uyarı sistemlerine dayalı mücadele zamanlaması ve direnç yönetimini gözeten fungusit uygulamalarının birlikte ele alınmasını gerektirmektedir. Fungal hastalıkların yanı sıra, yabancı otlar ve nematodlar da bölgede şeker pancarı verim ve kalitesini sınırlayan önemli etmenler arasındadır. Sivas ekolojik koşullarına uygun olarak uygulanan pancar–tahıl ekim rotasyonu, hastalık ve yabancı ot döngülerinin kırılmasına katkı sağlamakta; uygun yönetim koşullarında, buğday ve arpa ekimlerinde verim artışına olanak tanımaktadır.

Bu derlemede, Sivas ili koşullarında şeker pancarı üretiminin agroekonomik önemi ve yetiştirme özellikleri ortaya konulmakta; verim ve kaliteyi sınırlayan başlıca bitki koruma sorunlarının özellikle fungal hastalıklar, yabancı otlar ve nematodlar epidemiyolojisi ve zarar düzeyleri literatür ışığında değerlendirilmektedir. Ayrıca, sürdürülebilir şeker pancarı üretimi için sulama yönetimi ve ekim nöbeti gibi agronomik uygulamalarla entegre mücadele stratejilerinin tartışılması hedeflenmiştir.

Bitki Koruma Sorunları ve Entegre Mücadele Yaklaşımları

Şeker pancarında verim ve kaliteyi sınırlayan başlıca etmenler; yabancı otlar, hastalıklar ve zararlılardır. Şeker pancarı ve şeker kamışında biyotik faktörlere bağlı yıllık ürün kayıplarının %45,2'ye ulaşabildiği, bu kayıpların %16,5'inin zararlılardan, %16,5'inin hastalıklardan ve %12,2'sinin yabancı otlardan kaynaklandığı bildirilmiştir (Yiğit, 2001). Sivas koşullarında

sürdürülebilir şeker pancarı üretiminin sağlanabilmesi için entegre mücadele ilkelerinin düzenli ve sistematik biçimde uygulanması zorunludur. Entegre mücadele kapsamında; tarımsal ekosistemin izlenmesi, ekonomik zarar eşiği (EZE) değerlerin dikkate alınması, uygun kültürel önlemler, biyolojik ve biyoteknik yöntemlerin desteklenmesi ile kimyasal mücadelenin rasyonel ve hedefe yönelik kullanımı, uzun vadeli üretim ve sürdürülebilirlik açısından kritik öneme sahiptir.

Rhizoctonia Kök Çürüklüğü Hastalığı (*Rhizoctonia solani)*

Şeker pancarı, toprak kökenli birçok patojene karşı savunmasızdır. Basidiomycetes sınıfında yer alan *Rhizoctonia solani* (Wibberg ve ark.,)'nin neden olduğu kök çürüklüğü dünya çapında şeker pancarı üretiminde en önemli toprak kökenli hastalıklardan biridir. Şeker pancarı üretimi için giderek artan bir sorun haline gelmiş olan Rhizoctonia kök çürüklüğünden kaynaklanan verim kayıplarını azaltmak için tarımsal önlemler almak oldukça önemlidir (Holmquist ve ark., 2021). *R. solani* nin neden olduğu kök ve taç çürüklüğü, genellikle yetiştirme sezonunun ileri dönemlerinde, yapraklarda solma, kloroz ve yaprak saplarının tabanında koyu kahverengi lezyonlar gibi toprak üstü semptomlar şeklinde görülür. Kök ve taç çürüklükleri, yüksek sıcaklık ve düzensiz sulama-kabuklanma koşullarında hastalık şiddetlenir; söküm kayıpları artar (Barreto ve ark., 2020). Rhizoctonia kök çürüklüğü, hastalığı 22-35 °C arasındaki sıcaklıklarda nemli koşullarda optimum gelişir (Neher ve Gallian, 2013). Hastalık nedeniyle, ticari şeker pancarı tarlalarında %50 veya daha fazla verim kayıplarının olduğu, depolanmış köklerde şeker miktarını azalttığı ve fabrikada işlemede zorluklara yol açabildiği bildirilmiştir (Tallgren ve ark., 1999; Büttner ve ark., 2004). Jacobsen (2005) şeker pancarında yaptığı bir çalışmada *Rhizoctonia solani, Rhizoctonia crocorum* ve *Macrophomina phaseolina'nın* kök çürüklüğüne neden olarak, önemli miktarda zararlara neden toprak kökenli patojenler olduğunu bildirmiştir.

Çökerten: *R. solani* (AG IV) ile enfekteli bitkiler suya batırılmış gibi görünür. Gövdede ve toprak yüzeyinin hemen altında kararmalar şeklinde belirti verir ve belirtiler hipokotile doğru yayılma gösterir. Bu durumdaki fideler çoğunlukla solar ve ölür (Neher ve Galligan, 2011). Verim kayıpları, köklerin kaybından, köklerin bozulmasından dolayı azalan tonaj miktarından ve şeker oranının azalmasından kaynaklanmaktadır. Yapraklarda solma ve yaprak sapında koyu kahverenginden siyaha doğru renk değişikliği görülür. Zamanla yapraklar toprak yüzeyinde çöker ve ölür. Ölümden sonra yaprak sapları taça bağlı olarak kalır ve ölü yapraklar siyah rozet oluşturur (Neher ve Galligan, 2011).

Taç ve kök çürüklüğü: Enfeksiyon taçlarda, şeker pancarı köklerinde veya toprak yüzeyinin altında taç çürüklüğü şeklinde kendini gösterir. Hastalık enfeksiyon noktasından aşağı doğru yayılır. Hastalık ilerledikçe koyu renkli lezyonlar birleşerek dairesel ya da oval lekeler şeklini alır. Rhizoctonia kök çürüklüğü şeker pancarında ani solma yapabildiği gibi kalıcı solma şeklinde de kendini gösterebilir. (Harveson, 2008).

Kök belirtileri Hastalık şeker pancarı köklerinde koyu kahverengiden siyaha renk değişimine yol açarken bitkide kanserler ve çatlaklar da meydana getirebilir. Bitkide çürüyen kök dokuları katı haldeyken ikincil fungus ve bakteri istilası sonucu yumuşak hale gelebilir. Kök belirtileri genellikle oval şeklindedir, koyu lezyonlar ise dairesel olarak gelişir (Harveson, 2008).

Yaprak belirtileri Hastalık şeker pancarı bitkisinde bodur yaprak gelişimine, mat yaprak rengine, ani ve kalıcı yaprak solmasına neden olur. Solan dokuda sararma ve öncelikle yaşlı yapraklardan başlayan ölüm şeklinde kendini gösterir. Hastalığa yakalanan yaprak sapı zamanla koyu kahverengiden siyaha giden renk alır.

Hastalıkla mücadelede kültürel önlemlerin uygulanması önemlidir. Bu amaçla, patojenin konukçusu olmayan kültür bitkileri ile 4–5 yıl rotasyon yapılması, enfekteli bitki kısımlarının toplanması ve depolanmış ürünlere bulaşmayı engellemek için enfekteli köklerin uzaklaştırılması önerilmektedir. Etmenin kimyasal mücadelesi zordur ve ancak sınırlı alanlarda kısmen başarılı olabilmektedir (Mohammadi ve ark., 2003). Fungisitler (Tolclofos-methyl, Azoxystrobin, Flutolanil, Prothioconazole, Difenoconazole/Propiconazole, Pyraclostrobin, Trifloxystrobin, Pencycuron, Tebuconazole) Rhizoctonia kök çürüklüğü ve fide çökerten kontrolünde kullanılabilir (Kiewnick ve ark., 2001). Etmene karşı yapılan biyolojik mücadele çalışmalarında *Trichoderma* spp., *Gliocladium* spp., binükleit Rhizoctonia, *Pseudomonas* spp., *Bacillus* spp., *Streptomyces* spp. gibi antagonistlerle çalışmalar yürütülmüş ve etkili sonuçlar alınmıştır (Trillas ve ark., 2006).

Cercospora yaprak lekesi (*Cercospora beticola* Sacc.)

Şeker pancarında Cercospora yaprak lekesi, dünya genelinde yaygındır ve yol açtığı kalite/verim kayıpları nedeniyle en önemli yaprak hastalığı olarak kabul edilmektedir; sıcak ve nispi nemin yüksek seyrettiği üretim alanlarında önemli zararlara yol açar (Weiland & Koch, 2004; Skaracis ve ark., 2010). Özellikle ortalama sıcaklığın 20 °C ve üzerinde olduğu dönemlerde, yaprak ıslaklık süresinin uzun olduğu, yoğun yağış alan ya da yağmurlama sulama yapılan tarlalarda enfeksiyon riski önemli ölçüde artar (Khan ve ark., 2008; Skaracis ve ark., 2010; Stevanato ve ark., 2015).

Hastalık belirtileri tipik olarak yapraklarda mor-kırmızımsı kahverengi sınırlı, ortası açık gri renkte küçük dairesel lekeler şeklinde başlar; lekeler kısa sürede çoğalır ve birleşerek geniş nekrotik alanlara dönüşür. Hastalık ilerledikçe yapraklar kenardan merkeze doğru kurur ve ölür. Enfeksiyon çoğu zaman dış yapraklardan başlar, iç kısımlara doğru ilerleyerek tüm yaprakların kurumasına neden olur (Tan ve ark, 2023) Bitki, bu durumda taç (göbek) kısmından yeni yapraklar oluşturmaya yönelir; ancak bu büyüme kök gelişimine ayrılacak karbonu azaltır, kök iriliği ile şeker oranını (polar) düşürür (Weiland & Koch, 2004; Khan ve ark., 2008). Uygun iklim koşullarında ve yetersiz hastalık kontrolü durumunda, şeker veriminde belirgin düşüşler ve buna bağlı ekonomik kayıplar görülür. Hastalığın şiddeti bölgeden bölgeye değişmekle birlikte etmenle mücadele yapılmadığı taktirde şeker pancarının kök verimini % 26, ve şeker verimini %55'e kadar düştüğü bildirilmiştir. Etmen bir sonraki yıla taşınması, tarlada kalan bitki artıkları veya bulaşık tohumlarla olurken bitkiden bitkiye taşınma yağmur sularının sıçraması ve rüzgar etkisi ile gerçekleşir. Hastalıkla mücadelede, fungisit uygulamaları, dayanıklı çeşitlerin yetiştirilmesi ve ürün rotasyonunun birlikte uygulandı entegre mücadele esasına dayanır (Miller et al., 1994; Skaracis ve ark., 2010; Stevanato ve ark., 2015) Ancak, epidemi koşulları oluştuğunda yalnız kültürel önlemler çoğu zaman yetersiz kalır; zamanında ve doğru seçilmiş fungisitlerin kullanımı gereklidir (Khan ve ark., 2008; Stevanato ve ark., 2015). Erken uyarı eşiğine gelindiğinde hastalık için optimum koşullar geliştiğinde, her 100 yapraktan en az 5'inde tipik Cercospora lekesi saptanması (≈%5 yaprak enfeksiyonu) durumunda koruyucu ilaçlamaya başlanması önerilir (Khan ve ark., 2008; Sushmita ve ark, 2025). Hastalıkla mücadelede; sertifikalı temiz tohumluk kullanmak, tarlada görülen hastalıklı bitkilerin toplanıp yakılması, etkili yabancı ot mücadelesi yapılması ve en az 3 yıl süreyle ekim rotasyonu yapılması önerilmektedir. Hastalığın kimyasal mücadelesi yeşil aksam ilaçlaması şeklinde yapılır.

Rhizomania Kök Sakallanması Hastalığı

Rhizomania Kök Salkallanması hastalığı, *Polymyxa betae* vektörlüğünde Beet necrotic yellow vein virusun (BNYVV) neden olduğu ve şeker pancarı yetiştirilen tüm alanlarda görülen en tahripkar hastalıkların başında gelmektedir (Tamada ve ark., 1975; Rush, 2003; EFSA, 2020).

Vektör fungus, *P. betae* 1964 yılında ilk defa Keskin 1964 tarafından tanımlanmıştır. Etmen, Chenopodiaceae üzerinde zorunlu endoparazit olarak yaşar hastalık şeker pancarı yetiştirilen tüm bölgelerde büyük oranda görülmektedir (Keskin, 1964; Blunt ve ark., 1991). *P. betae* kalın duvarlı dinlenme yapıları ile uzun süre toprakta canlı kalabilir (Ertunç, 1998). Böylece virüs toprakta en az 15 yıl bulaşık kalabildiği ve vektörün virüsü çok uzun süre taşıyabildiği bildirilmiştir (Abe ve Tamada, 1986; Duffus, 1991; Rush ve Heidel, 1995). Hastalık Türkiye'de Marmara, Orta Karadeniz ve İç Anadolu bölgesinde varlığı bildirilmiş olup yayılış devam etmektedir (Kaya ve ark., 2019). BNYVV çoğu bitki patojeni virüs gibi RNA virüsüdür; RNA1–2 replikasyon ve hareket için zorunlu, RNA3–4 patojeniteye katkıda bulunur ve bazı soyların taşıdığı ek RNA5 yüksek saldırganlık ile direnç kırma kapasitesiyle ilişkilidir (EFSA, 2020; Tamada ve ark., 2021; Liebe ve Varrelmann, 2023).

Rhizomania kök sakallanması hastalığı, bulaşık toprak ve su hareketiyle, hasat artıklarıyla ve şeker fabrikalarının atık suları ile yayılabilir (Cariolle, 1987; Heijbroek, 1987; Asher, 1994). Erken dönem enfeksiyonu sonucu kökte yan köklerin aşırı çoğalması nedeniyle "sakallı kök" görüntüsü geç dönem enfeksiyonu sonucunda da köklerde çürüme ve taç bölgesinde görülen kahverengilileşme hastalığın tipik simptomudur. Ayrıca hasta bitkilerin iletim demetlerinde renk değişimi, yapraklarında solma, sararma şeklinde belirtiler görülür (Rush ve Heidel, 1995). Hastalık nedeniyle enfeksiyon şiddetine bağlı olarak kökte %30–90 ve şeker veriminde ise %70'e varan kayıplara neden olduğu bildirilmiştir (Asher, 1993; Asher ve Kerr, 1996; Putz ve ark., 1990; Whitney ve Duffus, 1991; Rush ve Heidel, 1995). Hastalıkla mücadelede en önemli yöntem dayanıklı çeşit yetiştirmektir (Asher, 1994; Richard-Molard, 1996). Dayanıklı çeşit geliştirmek amacıyla yapılan ıslah çalışmaları uzun soluklu çalışmalar olup, Rz1 ve Rz2 genleriyle ve bunların kombinasyonları ile (Rz1+Rz2) tarladaki kontrol şansının arttığı, RNA5 taşıyan popülasyonlara karşı olumlu sonuçlara varıldığı bildirilmiştir. (Wetzel ve ark., 2021; Müllender ve ark., 2022). Hastalıkla kültürel mücadelede; ürün rotasyonu, iyi drenaj ve toprak havalanması ile erken ekim (Tosic ve ark., 1985), sulama suyu yönetimi, kendi gelen ve yabani pancarların eradikasyonu oldukça önemlidir. Tek başına rotasyon toprakta uzun süre canlı kalan vektörü kontrol etmede yetersiz kalabilmektedir (Abe ve Tamada, 1986; Rush ve Heidel, 1995; EFSA, 2020).olive

Fusarium Kök Çürüklüğü (*Fusarium* spp)

Fusarium spp, şeker pancarı dahil olmak üzere birçok tarımsal üründe ciddi zarara neden olan toprak kaynaklı patojenlerden biridir. Fusarium spp. erken dönemde; çökerten ve kök çürüklüklerine neden olurken geç dönemde ise bitkilerinin yeşil aksamında genel bir kloroz, solgunluk ve yaşlı yapraklarda kurumalar şeklinde belirti verir. Hastalıktan etkilenen bitkilerin köklerinde iletim demetlerinde renk değişikliği görülür. Şeker pancarındaki kök çürüklüğü hastalıkları, kök-gövde verimi ve şeker oranı önemli ölçüde azaltır (Cao ve ark., 2018). Tarlada optimal bir kök-gövde ve şeker verimi sağlamak için şeker pancarının kök çürüklüğüne neden olan toprak kaynaklı patojenlerinden korunması gerekmektedir (De Lucchi ve ark., 2017).

Külleme *Erysiphe betae*

Şeker pancarında külleme (*Erysiphe betae*) hastalığı dünya genelindeki şeker pancarı üretimi yapılan tüm alanlarında görülmektedir. Hastalık nedeniyle elde edilen üründe şeker oranında %30'lara varan kayıplar açıklamıştır (Francis, 2002). Hastalık oluşumu için en uygun zaman, kurak hava koşullarının yanı sıra yüksek gündüz fakat düşük gece sıcaklıkları, yani gece-gündüz sıcaklık farkının fazla olduğu periyotlardır. Hastalığın ilk belirtileri; genellikle yaşlı yaprakların alt yüzeyinde küçük, dağınık ve seyrek beyaz miselyum kitleleri halinde seyreder. İlerleyen zamanlarda tüm yaprak yüzeyi beyaz pudra serpilmiş gibi görünür. Hastalık uygun ortam koşullarında hızlı bir şekilde gelişerek bütün yaprak yüzeyini kap Kandilci (2006) ise

Adana'da yapmış olduğu bir araştırmada, Türkiye'de ki şeker pancarı ekim alanlarının şeker pancarı olgunlaşma evresinde yoğun bir şekilde külleme hastalığının epidemi yaptığını açıklamıştır.

Yabancı Otlar

Yabancı otlar, şeker pancarı kültürünün en önemli sorunlarından biridir. Şeker pancarı, ilk büyüme döneminde yabancı ot rekabetine karşı son derece hassastır, bu nedenle bu aşamada etkili yabancı ot kontrolü çok önemlidir. (Jalali & Salehi 2013; Marwitz et al 2014). Kültür bitkileriyle, su, besin maddesi ve ışık yönünden rekabete giren yabancı otlar; şeker pancarının başlangıçtaki gelişme hızının yavaş ve rekabet kabiliyetinin zayıf olması nedeniyle ürünün kalite ve kantitesi üzerinde büyük zararlara neden olmaktadır (Güncan, 1993; Özer ve ark., 2001). Dünyada şeker pancarında yabancı otlardan ileri gelen ürün kaybı ortalama %5,8 iken, bu kayıp Türkiye'de ortalama %6-40 arasında değişmektedir (Güncan 2010).

Ekimden sonra 8 hafta içinde veya şeker pancarı bitkisinin iki yaprak aşamasına 4 hafta içinde çıkan kontrolsüz yıllık yabancı otlar, kök verimlerini %26 ila %100 arasında azaltabilir (Schweizer ve Dexter 1987; Rosso vd. 1996). Farklı zamanlarda çıkan yabancı otların şeker pancarı verim kayıplarına etkisi üzerine sürenin etkisiyle ilgili veriler, gereken yabancı ot kontrol sürelerini belirleme temelini oluşturur. Şeker pancarı tarlalarında bulunan yabancı otların yaklaşık %70'i geniş yapraklı türlerden oluşurken, %30'u dar yapraklı türlerdir (May ve Wilson 2006). Şeker pancarı üretiminde sorun olan yabancı otlar arasında sirken (*Chenopodium album*) yabani yabani hardal (*Sinapis arvensis*) ile horozibiği (*Amaranthus* spp.). ve tarla sarmaşığı (*Convolvulus arvensis*) gibi hızlı büyüyen yazlık türler öne çıkar.

Küsküt (*Cuscuta campestris*), Cuscuta cinsi, Convolvulaceae familyasına ait yıllık ve tam parazit bir bitkidir. C. campestris'in şeker pancarı, havuç, biber, sarımsak, soğan, domates, baklagiller, kavun, karpuz, patates, üçgül ve yoncada zarar verdiği ve bazı durumlarda zarar oranının %50-90 arasında değiştiği bildirilmektedir (Dawson et al. 1994, Lanini and Kogan 2005, Lian et al. 2006, NadlerHassar and Rubin 2003, Parker and Riches 1993). Şeker pancarı veriminde de 3.5-4 ton/ha azalmaya neden olmuştur (Aly et al. 2003).

Yabancı otlarla mücadelede; Temiz tohum, ekipman hijyeni, tarla kenarı ve su kanalı bakımının düzenli yapılması. Uygun ekim sıklığı ve sıra aralığı, rekabet gücü yüksek sıra üzeri bitki yoğunluğu dikkat edilmesi gereken kültürel mücadele yöntemleridir. Toprak işleme ile tek yıllık yabancı otların mücadelesinde daha iyi sonuç alınmaktadır. Çok yıllık yabancı otlarda ise yüzeysel köklü olanlar sürümle azaltılabilir. Ancak bunların toprak altı organları tarladan uzaklaştırılarak imha edilmelidir. Derin köklü çok yıllık yabancı otlar (Tarla sarmaşığı, köygöçüren, ayrık vs.), birkaç yıl üst üste yetiştirme dönemi süresince tekrarlanacak toprak işlemesi ile baskı altına alınabilir. Ekim nöbeti uygulanmalıdır. Kimyasal mücadelede ise, Pre-/post-emergence programlarının rotasyon ilkelerine göre planlanması; etki mekanizması farklılığına dayalı ardışık uygulamalar ile direnç riskinin azaltılması. Herbisit uygulaması, kullanılacak ilaçlara bağlı olarak ekim öncesi, çıkış öncesi, çıkış sonrası ve çıkış öncesi+çıkış sonrası olmak üzere dört şekilde yapılır (Tagem,2020).

Şeker Pancarı Zararlıları

Şeker Pancarı Kist Nematodu (*Heterodera schachtii*),

Şeker pancarı kist nematodu (*Heterodera schachtii*), şeker pancarında en önemli nematod zararlılarından biri olarak kabul edilir ve çoğu şeker pancarı yetiştirme alanında bulunur (Stevanato ve ark., 2015). Sarı pancar kist nematodu (*Heterodera betae*) daha az yaygın olsa da pancara zarar verdiği tespit edilmiştir (Vandenbossche ve ark., 2011). Nematodlar

(*Heterodera schachtii*): bitkide kök gelişimini baskılar; verim ve polarizasyonda düşüşe neden olur. Bitkinin yaşı, mevsim sıcaklığı ve popülasyon yoğunluğuna bağlı olarak bitkide büyüme geriliği ve verim kaybı görülür; sıcak dönemlerde yapraklarda belirgin pörsüme/solma meydana gelir. Kök sisteminde, özellikle ince yan köklerde aşırı saçaklanma ve çalılaşmalar ortaya çıkar; yoğun bulaşıklık durumunda bitki tamamen ölebilir. Şeker pancarı kist nematodu ile bulaşık topraklarda yetişen bitkilerde, genellikle bodurlaşma görülür, bitkinin gelişmesi zayıflar, yapraklar küçük kalır. Günün sıcak saatlerinde kökler vasıtasıyla normal su alım düzeni bozulduğundan, solgun bir durum arz ederler. 75 g toprak içindeki her bir canlı kist, dekarda 4 kg şeker ve 25 kg pancar ağırlığı kaybına neden olmakta ve şeker pancarı tarlalarında %50'ye varan ürün kaybı meydana getirebilmektedir. Şeker pancarı kist nematodu karantina etmeni olmamasına rağmen kist nematodları bulaştıktan sonra eradike edilmesi çok zor bir grup olduğundan, karantina tedbirlerinin üzerinde önemle durulmalıdır. Ülkemizde ve bölgede yaygın olarak görülen bu zararlının mücadelesinin zorluğu nedeniyle üretim alanlarında 4 yıllık zorunlu münavebe uygulanmaktadır.

Zararlılar

Bozkurtlar; *Agrotis ipsilon, Agrotis segetum* (Lepidoptera: Noctuidae), tarlada bitki çıkışını takiben toprak seviyesinin hemen altında köklerin kesildiği görülebilir , kök boğazının altından kesilen veya derince yaralanan bitkilerde solgunluk görülmesi, yaprakların sap dibinden kesilmesi veya yaprakların sadece orta damarlar kalacak şekilde yenilmesi şeklinde zarar verirler.

Kalkan Böcekleri (*Cassida* spp.), Ana zararı larvalar yaprakların alt veya üst yüzeylerinde küçük yuvarlak (1-2 mm) yüzeysel yenikler şeklinde yaparlar.

Yaprak bitleri (*Myzus persicae, Aphis fabae*): Emgi zararı ve virüs vektörlüğü yoluyla kaliteyi düşürür.

Yaprak galerisi sinekleri (*Pegomya hyoscyami var. betae*): Yaprak dokusunda galeriler açarak fotosentezi sınırlar.

Sonuç ve Öneriler

Sivas, farklı ilçelere yayılmış geniş şeker pancarı ekim alanları, güvenilir sulama olanakları ve sözleşmeli üretim–fabrika bağlantılarıyla Türkiye'nin şeker pancarı ekonomisi açısından stratejik bir konuma sahiptir. Ancak bu potansiyelin tam olarak değerlendirilebilmesi, fungal hastalıklar, yabancı otlar ve nematodlar başta olmak üzere tüm bitki koruma sorunlarının entegre mücadele ilkeleri doğrultusunda yönetilmesine bağlıdır. En yüksek kazanç; sulama, çeşit seçimi, ekim nöbeti, toprak işleme, yabancı ot kontrolü ve fungusit uygulamalarının, epidemiolojik veriler ve erken uyarı sistemleriyle desteklenen doğru zamanlama çerçevesinde planlanması ile sağlanacaktır.

Geleceğe yönelik sürdürülebilir ilerleme; verim ve polarizasyonu yüksek üretim modellerinin benimsenmesine, entegre bitki koruma uygulamalarının yaygınlaştırılmasına ve çiftçi eğitimlerinin güçlendirilmesine bağlıdır. Bunun için, sulama verimliliğini artıran teknolojilerin benimsenmesi, hastalıklara dayanıklı/toleranslı çeşitlerin kullanımının desteklenmesi, pancar–tahıl ekim rotasyonlarının bölge koşullarına uyarlanması önem taşımaktadır. Sonuç olarak, Sivas'ta şeker pancarı üretim zincirinin; entegre mücadele stratejilerini benimseyen su kaynaklarını koruyan, çiftçi gelirini istikrara kavuşturan bir yaklaşımla yürütülmesi, hem bölgesel rekabet gücü hem de uzun vadeli tarımsal sürdürülebilirlik için temel bir gereklilik olarak değerlendirilmektedir.

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MAVİ YEMİŞ (*Vaccinium corymbosum*): TÜRKİYE VE DÜNYADAKİ ÇALIŞMALAR, HASAT ÖNCESİ VE SONRASI HASTALIKLAR VE MÜCADELE YÖNTEMLERİ

BLUEBERRY (*Vaccinium Corymbosum*): STUDİES IN TURKEY AND WORLDWİDE, PRE- AND POST-HARVEST DİSEASES AND CONTROL METHODS

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ÖZET

Mavi yemiş (*Vaccinium corymbosum*), yüksek antioksidan ve anti-enflamatuar içeriği sayesinde fonksiyonel gıdalar arasında ön plana çıkan değerli bir küçük meyve türüdür. Ancak bu ürün hem vejetasyon süresince hem de hasat sonrası dönemde başta fungal ve bakteriyel etmenler olmak üzere çeşitli patojenlerin saldırısına maruz kalmakta; özellikle *Botrytis cinerea* kaynaklı gri küf ve *Colletotrichum* spp. neden olduğu antraknoz gibi hastalıklar kalite kaybına ve ticari değerinde azalmaya yol açmaktadır. Hastalıklara karşı geleneksel olarak sentetik fungisitler en yaygın kontrol aracı olarak kullanılmakla birlikte, bu kimyasalların insan sağlığı, çevre ve kalıntı problemleri gibi riskleri nedeniyle sürdürülebilir alternatif yaklaşımlar giderek daha fazla önem kazanmaktadır. Son yıllarda, modifiye atmosfer koşulları, ultraviyole (UV) ışın uygulamaları, kitosan ve uçucu yağlar gibi bitkisel kökenli antimikrobiyal bileşikler ile biyolojik mücadelede kullanılan mikrobiyal antagonistler gibi çevre dostu stratejiler ön plana çıkmaktadır. Bu derleme, Türkiye ve dünyada Mavi yemiş üretiminde karşılaşılan başlıca patojenleri analiz etmeyi; ayrıca hem hasat öncesi hem de hasat sonrası dönemde uygulanan kimyasal, fiziksel ve biyolojik kontrol yöntemlerini, bunların muhtemel etki mekanizmalarını ve meyve kalitesi üzerindeki etkilerini bütüncül bir yaklaşımla ele almayı amaçlamaktadır. Bu çalışma ile Mavi yemiş üretiminde sürdürülebilir hastalık yönetimi uygulamalarına katkı sağlanması hedeflenmektedir.

Anahtar kelimeler: *Vaccinium corymbosum*, hastalık etmenleri, Mücadele yöntemleri biyolojik kontrol, sürdürülebilir tarım

1.Giriş

Türkiye, sahip olduğu farklı iklim kuşakları ve zengin ekolojik çeşitliliği sayesinde, çok sayıda meyve türünün farklı bölgelerde ve mevsimlerde başarıyla yetiştirilebildiği nadir ülkelerden biridir (Ercişli, 2004). Bu çeşitlilik içerisinde yer alan Mavi yemiş (*Vaccinium* spp.), son yıllarda hem dünyada hem de Türkiye'de artan bir ilgi görmektedir. Özellikle,yüksek boylu bir tür olan *Vaccinium corymbosum* içerdiği biyolojik aktif bileşikler açısından zengin bir profille ön plana çıkmaktadır. Bu bileşikler arasında yer alan antikanserojen etkili bir fenol olan ellajik asit, flavonoid sınıfına ait antosiyaninler, kersetin, kaempferol ve mirisetin gibi bileşenler güçlü antioksidan ve anti-inflamatuar özellikler göstermektedir (Michalska ve Łysiak, 2015). Modern yaşamın getirdiği oksidatif stres ve kronik hastalık yüküne karşı koruyucu etkileri, Mavi yemişnin tüketimini teşvik eden başlıca etkenlerden biridir (Kılıç Topuz, 2019; Tosun ve Yüksel, 2003).

Tarım açısından bakıldığında, *Vaccinium* spp. türleri küçük meyveli, mavimsi-mor (yüksek boylu) veya kırmızı (alçak boylu) tanelere sahip çalı formlu bitkilerdir. Kültürü yapılan başlıca türler; yüksek boylu (*V. corymbosum*), alçak boylu (*V. angustifolium*) ve tavşan gözü (*V. virgatum*) Mavi yemiş çeşitleridir (Defilippi ve ark., 2017). Meyvenin küçük yapısı ve ince kabuğu, hasat öncesi ve sonrası dönemde özellikle sıcaklık ve bağıl nem gibi çevresel faktörlere karşı duyarlılığını artırmakta ve bu koşullar altında fungal ve bakteriyel patojenlerin gelişimiyle %20'lere varan ürün kayıpları meydana gelebilmektedir.

TÜİK (2023) verilerine göre, 2022 yılı itibarıyla Türkiye'de 4.197 dekar alanda yaklaşık 5.200 ton Mavi yemiş üretimi gerçekleştirilmiştir. Yetiştiricilik esas olarak Karadeniz, Marmara ve Doğu Anadolu bölgelerinde yoğunlaşmakta olup, bu bölgelerdeki düşük pH'lı (asidik) toprak yapısı ve serin iklim koşulları, bitkinin morfolojik ve fizyolojik gereksinimlerini büyük ölçüde karşılamaktadır. Dünya genelinde ise ABD, Kanada, Şili, Polonya ve Almanya başta olmak üzere birçok ülkede üretim yoğun şekilde artmakta ve FAOSTAT (2023) verilerine göre küresel Mavi yemiş üretimi 1,7 milyon metrik tonu aşmış durumdadır. Türkiye'nin bu potansiyelden daha fazla pay alabilmesi, entegre üretim sistemlerinin geliştirilmesi ve sürdürülebilir hastalık yönetimi stratejilerinin benimsenmesiyle mümkün olacaktır. Mavi yemişin üreticiler tarafından benimsenmesinde; erkencilik (dikimden sonraki yılda ürün verebilme), sanayiye uygun işlenebilirlik, aile işletmeleri için uygunluk, estetik meyve görünümü ve yüksek birim fiyat gibi önemli avantajlar etkili olmaktadır (Ağaoğlu, 1986; Kılıç Topuz, 2019).Mavi yemişe yönelik küresel talebin hızla arttığı günümüzde, hastalık etmenlerinin biyolojisini ve epidemiyolojisini anlamak, bitkinin savunma mekanizmalarını çözümlemek ve entegre mücadele stratejileri geliştirmek temel bir gereklilik haline gelmiştir.

Bu derleme, hasat öncesi ve sonrası dönemde karşılaşılan başlıca patojenleri, hastalıkların etki mekanizmalarını, konukçu savunma tepkilerini ve mevcut kontrol stratejilerini literatür temelli bir yaklaşımla incelemeyi amaçlamaktadır. Böylece hem akademik bilgi birikimine katkı sağlanması hem de Mavi yemiş üretim sistemlerine uygulanabilir öneriler sunulması hedeflenmektedir.

2. Mavi Yemişte Önemli Patojenler

Mavi yemiş üretim sistemleri hem vejetatif büyüme dönemi boyunca hem de hasat sonrası süreçte çeşitli fitopatojenlerin baskısıyla karşı karşıya kalmaktadır. Özellikle fungal, bakteriyel ve viral kaynaklı hastalıklar, uygun çevresel koşullarda epidemi oluşturarak meyve kalitesini ve pazarlanabilirliğini ciddi biçimde tehdit etmektedir. Bu bölümde, Mavi yemişde en yaygın görülen ve ekonomik kayıplara neden olan başlıca patojenler, biyolojik özellikleri ve enfeksiyon dinamikleri açısından analiz edilmiştir.

2.1. Fungal Hastalık etmenleri

2.1.1. Gri küf (*Botrytis cinerea*)

Gri küf (*Botrytis cinerea*), 1400'den fazla bitki türünü etkileyen, geniş bir konukçu yelpazesine sahip nekrotrofik bir fungustur hem hasat öncesi hem de hasat sonrası Mavi yemişi etkileyen önemli bir patojendir (Roca-Couso ve ark, 2021; Rui ve ark, 2023; Li ve ark, 2023). *B. cinerea,* Mavi yemişte hem çiçeklenme hem de meyve olgunlaşma döneminde özellikle %90'dan fazla bağıl nem ve 15–20°C sıcaklıkta optimum gelişme gösterir. Gri renkli miselyal örtü ve sporulasyon ile karakterize edilen bu hastalık, hasat sonrası taşımada ve depolama sürecinde de meyvelerin çürümesine yol açar. Mavi yemişte bu etmenle oluşan kayıplar %30 40'a kadar çıkabileceği rapor edilmiştir (Polashock, ve ark. 2017). Bu hastalığın belirtileri çiçeklerde, yapraklarda ve meyvelerde görülür. Başlangıçta meyvede küçük, sert, açık kahverengi lezyonlar gelişir ve bunlar hızla genişler ve gri renkli misel tabakasıyla kaplanır. Çiçeklerde çürüme semptomları görülür ve şiddetli enfeksiyonlar sonucunda tamamen solmaya yol açar. Yapraklarda kahverengi-gri lezyonlar oluşur ve yüksek nem koşulları altında bu lezyonlarda gri miselyum ve konidi kitleleri gelişebilir (Kwon ve ark., 2011). Gri küf, Mavi yemişte yalnızca doğrudan çürümeye neden olmakla kalmaz, aynı zamanda su kaybını ve besin bozulmasını hızlandırarak raf ömrünü de azaltır. Gri küf, büyüme ve meyve gelişiminin ilk aşamalarında latent bir enfeksiyon süreci gösterir ve hasat sonrası dönemde belirtiler gösterir. Olgun meyvelerde hastalık belirtileri, meyvenin yumuşaması, meyve suyu salınımı, susuz kalma ve gri renkli miselyum kütlesinin gelişmesiyle karakterizedir (Rivera ve ark., 2013). *B. cinerea,* toksin üretimi, oksijene reaktif türler, parçalayıcı enzimlerin üretimi ve programlanmış hücre ölümü indüksiyonu gibi virülans faktörlerini aktive ederek meyve dokusunda ölüme neden olur (Williamson ve ark., 2007). In vitro kültürde, başlangıçta beyaz koloniler oluşturur ve daha sonra renk gri veya kahverengiye döner ve siyah sklerotlar üretir. Konidioforlar ince ve dallıdır, konidia ise oval ila yuvarlak şekillidir (Li ve ark,2011; Chean ve ark, 2013; Saito ve ark,2016; Apolonio- Rodríguez ve ark., 2017). Işık mikroskobu altında, uzun konidioforlar, septalı, pürüzsüz, apikal olarak dallanmış ve konidia demetleri görülebilir. Konidia, yaklaşık 8–15 µm çapında, tek hücreli, oval, pürüzsüz ve küresel formdadır (Fillinger ve Elad, 2015). Fungus, düşük sıcaklıklarda (0–4 °C) ve nemli koşullarda aktif kalır ve bu da Mavi yemişin hasat sonrası depolanması sırasında %60–100 gibi yüksek gri küf görülme oranlarına yol açar (Mamode ve ark., 2021).

Türkiye'de Akdeniz/Doğu Anadolu bölgelerinin bahar ve yaz dönemlerinde nemli gece koşulları göstermesi nedeniyle, *B. cinerea'*nın hem hasat öncesi çiçek dönemi hem de hasat sonrası süre için potansiyel risk oluşturmaktadır. Latent enfeksiyonlara karşı erken uyarı sistemlerinin geliştirilmesi hastalıkla mücadelede önemli bir faktör olarak görülmektedir.

Gri küf yönetimi: Hasat öncesi hava sirkülasyonunun artırılması, hasat sonrası hızlı soğutma, UV-C ışınlama, kitosan kaplama ve biyolojik ajanlar (*Trichoderma harzianum* vb.) kullanımı olarak sıralanabilir.

2.1.2. Antraknoz (*Colletotrichum* spp.)

Colletotrichum acutatum ve *C. gloeosporioides* türleri Mavi yemişte antraknoz enfeksiyonlarının başlıca etmenleri arasında yer alır. Hastalık nemli ve sıcak iklim koşullarında hızla yayılır. Meyvelerde batık lekeler ve meyve çürüklüğü şeklinde görülür. Yapraklarda ise kıvrılma ve erken dökülme söz konusu olabilir. Mavi yemişte antraknoz kaynaklı kayıplar %10 20 düzeyinde bildirilmiştir. Mavi yemişler, çiçeklenmeden hasada kadar herhangi bir anda enfekte olabilir. *Colletotrichum* türleri, meyve olgunlaşmaya başlayana kadar latent evrede kalır. Mavi yemişnde antraknozun ana belirtisi, hasat sırasında ve sonrasında meyvenin

çürümesidir. Bu çürüme, meyve yüzeyinde çökük alanlar ve ardından pembe veya somon rengi konidial kitle yayan acervuli oluşumuyla kendini gösterir (Siddiqui ve Ali, 2014). İnvitro koşullarda *Colletotrichum* spp. gelişmesi 18 ila 30 °C arasında gerçekleşir. Koloni gelişimi genellikle pamuksu beyazdan griye kadar değişen bir renge sahiptir ve türe bağlı olarak renkleri değişen eş merkezli halkalar şeklinde büyür (Bordoh ve ark., 2020).

Antraknoz Yönetimi. Hastalık öncelikle fungisit uygulamasıyla kontrol altına alınır. Uygulamalar tam çiçeklenme döneminde başlatılmalı ve 7-10 günlük aralıklarla devam ettirilmelidir. Meyve salkımları etrafında iyi bir hava sirkülasyonu önerilir. Uygun hava koşullarında hastalıklı meyveden sağlam meyvelere hızlı yayılmayı önlemek için meyveler sık sık toplanmalıdır. Yoğun azotlu gübreleme, hastalık insidansını artırma eğilimindedir. Berkeley, Bluecrop, Blueray, Coville ve Jersey oldukça hassastır bu nedenle hastalığa dayanıklı çeşitlerin dikimi tercih edilmelidir.

2.1.3. Meyve çürümesi (*Alternaria* spp.)

Alternaria spp. meyveye yaralar, doğal açıklıklar veya doğrudan konukçunun kütikülündeki bir yırtık yoluyla nüfuz edebilen fırsatçı saprofit bir fungustur (Troncoso-Rojas ve ark., 2014). Meyve çürüme belirtileri, meyvede koyu ve çökük yaralar, beyazdan yeşilimsi griye kadar miselyum ve yeşil zeytin konidial büyümesi ile karakterizedir. (Zhu ve Xiao, 2015). *Alternaria* spp., bitki patolojisini ve gıda güvenliğini etkileyen çeşitli toksinler içeren ikincil metabolitler üretir. Bu toksinler arasında en önemlileri tenuazonic asit, alternariol ve alternariol monometil eterdir (Munitz ve ark., 2013). *Alternaria* spp, 20 ila 30 °C arasında, optimum gelişme gösterir, koloniler genellikle koyu yeşil renktedir ve merkezlerinde hif kilitleri bulunan pamuksu bir görünüme sahiptir (Zhu ve Xiao, 2015). Sporlar oval şekilli olup, enine duvarlar ve dikeylerle bölünmüştür, el bombasını andırır ve boyutları türe bağlı olarak 13 ila 15,0 µm arasında değişir.

Hastalık Yönetimi: *A. alternata* gibi türler, Mavi yemişte geç dönem yaprak lekeleri ve meyve çürümeleri oluşturabilir. Meyvede koyu renkli, dairesel lekelerle karakterize olur. Özellikle depolama sürecinde latent enfeksiyonlar aktive olabilir. Hasattan sonra soğuk zincirin bozulmaması, meyvelerde biyofilm kaplama ve fitokimyasallarla koruma mücadelede önerilmektedir.

2.1.4. Mumya meyvesi (*Monilinia vaccinii-corymbosi*)

Bu hastalık genellikle her yıl görülür, ancak şiddeti yıldan yıla büyük ölçüde değişir. Mayıs ayındaki serin ve yağmurlu hava, fungusun enfeksiyonunu kolaylaştırır. Patojen *Monilinia vaccinii-corymbosi'nin* iki enfeksiyon evresi vardır. Kışlayan askosporlar, yeni çıkan tomurcukları enfekte ederek yaprak ve sürgün yanıklığına neden olur. Bu enfekte dokuda üretilen konidyumlar daha sonra çiçekleri ve genç meyveleri enfekte eder. Enfekte meyveler açık ten rengi veya pembedir ve sertleşen meyveler buruşup yere düşer.

Mumya meyvesi hastalığının yönetimi. Hastalığın yönetimi birkaç strateji içerir, en önemlisi sanitasyondur. Mumyalar tırmıklanıp küçük dikimlerde atılmalıdır. Hassas Bluehaven, Bluegold, Coville, Northblue ve Sierra çeşitlerin dikiminden kaçınılmalıdır. Bluejay, Bleucrop, Darrow, Duke, Elliott, Jersey ve Stanley hastalığın sürgün yanıklığı evresine dayanıklıdır. Fungisit uygulamaları birincil enfeksiyona karşı hedeflenmelidir; yeşil uç büyüme aşamasında ilk uygulama 10 gün sonra ikinci bir uygulama ile takip edilmelidir. İkincil enfeksiyonu kontrol etmek için çiçeklenme sırasında ek fungisitler uygulanabilir. Genel olarak, bitkinin toprak üstü kısmını etkileyen fungal hastalıklar, bitkilerin etrafında iyi hava sirkülasyonu sağlamak için doğru dikim ve düzenli budama ile daha etkili bir şekilde yönetilebilir. Ayrıca, bitkileri sularken damla sulama tercih edilir. Yağmurlama sulama kullanılıyorsa, yaprakların, çiçeklerin ve meyvelerin hızlı kurumasını sağlamak için bu uygulama sabahın erken saatlerinde yapılmalıdır.

2.1.5. Phomopsis dal yanıklığı (*Phomopsis vaccinii*)

Hastalık, bitkiler soğuk veya kuraklık hasarı nedeniyle strese girdiği dönemlerde daha sık görülür. *Phomopsis vaccinii* gövdelerde küçük kanserler oluşturabilir veya tüm dallar, özellikle gövdedeki birkaç lezyon birbiriyle birleştiğinde dallarda ölüm görülebilir. Patojen ayrıca nadiren meyve çürümesine de neden olabilir.

Phomopsis dal yanıklığının yönetimi: Hastalık, yanlış budama veya toprak işlemeden kaynaklanan bitki hasarlarından kaçınılarak yönetilebilir. Kuraklık stresinden kaçınmak için bitkiler sulanmalıdır. Büyüme mevsimi boyunca fungisit uygulamaları inokulum baskısını azaltmaya ve enfeksiyonu önlemeye yardımcı olsa da, en önemli fungisit uygulaması uyku halindeki kireç-kükürt uygulamasıdır. Sonbaharda yaprak dökülmesinden sonra uygulanabilir, ancak tomurcuklar uyku halinden çıkmadan önce kış sonu veya ilkbahar başında uygulandığında daha etkilidir. Tomurcuklar büyümeye başladıktan sonra uygulamadan kaçınılmalıdır, aksi takdirde genç doku zarar görür. Sezon sonu büyümesi engellenmeli ve doğru gübre kullanımıyla bitkilerin erken sertleşmesi teşvik edilmelidir. Dayanıklı olduğu bilinen çeşitlerin dikimine özen gösterilmelidir.

2.1.6. Phytophthora kök çürüklüğü (*Phytophthora cinnamomi*)

Phytophthora kök çürüklüğü (*Phytophthora cinnamomi*), Mavi yemiş tarlasındaki drenajı yetersiz alanlarda daha fazla görülür. Kök sistemleri patojen tarafından enfekte edilip kök miktarı azaldıkça, bitkiler sonunda bodurlaşıp renksizleşecek ve meyve üretimi önemli ölçüde azalacaktır. Bitkinin tamamı, bazen tek bir yetiştirme sezonu içinde ölebilir. Etkilenmiş bitkiler seyrekleşmeye başlar ve her yıl daha az sürgün oluşturur. Enfekte bitkiler genellikle yapraklanır, çiçek açar ve meyve tutmaya başlar; ancak meyveler olgunlaşmadan önce sürgünler ölür, yapraklar kırılgan hâle gelir ve sararır; üzerinde kahverengimsi-kırmızı çizgiler görülür. Gelişmekte olan meyveler kurur ve buruşur. Hastalık etmeni *P. Cinnamomi*, toprakta doğal olarak bulunabilir, uzun yıllar canlılığını koruyabilir, sulama suyu ile; makineler, aletler, ayaklar ve enfekte bitkilerle hızla yayılabilir.

Phytophthora kök çürüklüğünün yönetimi. Hastalık, doğru yer seçimi ile önlenebilir. Ağır killi topraklar ve uzun süre su birikintisi olan alçak alanlara dikim yapılmamalıdır. Tarlanın sorunlu bölgelerinde drenaj iyileştirilmelidir. Geçmişte kök çürüklüğü sorunu yaşanmışsa veya drenaj optimumdan düşükse, ekim sırasında Metalaxyl (Ridomil) veya Fosetyl-Al (Aliette) kullanılmalıdır. Enfekteli plantasyonlarda kök çürüklüğünü kontrol edebilecek fungisitler mevcuttur; ancak bu fungisitler oldukça pahalıdır ve hastalığı kontrol etmede, yükseltilmiş yastıklar ve dayanıklı çeşitler kullanımı kadar etkili değildir.

2.1.7. *Penicillium* spp.

Penicillium expansum, hasat sonrası çürüklükte sorumlu en yaygın türlerdendir. Özellikle soğuk depolama sırasında düşük sıcaklık toleransı ile gelişebilir. Mikotoksin (patulin) üretme potansiyeli açısından halk sağlığı için de risk teşkil eder.

Hastalık Yönetimi: Yüzey dezenfeksiyonu, kontrollü atmosfer (CA) teknolojileri kullanmak önerilmektedir.

2.1.8. *Cladosporium* spp.

Mavi yemişte yaprak ve meyve üzerinde siyah leke oluşumuna neden olabilir. Özellikle nemli koşullarda hızlı gelişim gösteren *Cladosporium herbarum*, estetik kaliteyi düşürerek pazarlanabilirliği azaltır.

2.2. Bakteriyel Hastalık etmenleri

Pseudomonas syringae* ve *Xanthomonas spp.

Yapraklarda nekrotik lekelere, sürgün uçlarında kurumaya ve çiçek yanıklıklarına neden olabilen bakteriyel hastalıklar, özellikle ilkbahar yağışları ve dolu sonrası yaralanmalarla yayılmaktadır. Türkiye'de henüz sınırlı raporlanmış olmakla birlikte, ABD ve Avrupa ülkelerinde ciddi ekonomik kayıplara neden olmaktadır. Hastalıkla mücadele stratejisi: Bakırlı preparatlar, biyolojik ajanlar (*Bacillus subtilis*), enfekte doku uzaklaştırması olarak sıralanabilir.

Mavi yemişin hasat sonrası kayıpları, toprak veya su yoluyla bulaşabilen *Salmonella typhimurium, Escherichia coli* ve *Listeria monocytogenes* gibi Gram pozitif veya Gram negatif patojenik bakterilerin saldırısından da kaynaklanmaktadır (Zhang ve ark., 2021). Bu bakteriler, su, toprak veya hava yoluyla yayıldıktan sonra bitkiye doğal açıklıklar veya yaralar yoluyla girebilir. Ayrıca Mavi yemişin üretimi ve hasat zinciri sırasında, meyvenin bu patojenler tarafından kontaminasyonunun çeşitli kaynakları vardır (Cao ve ark., 2017). Fungal patojenlerden daha az ölçüde etkili olsa da, bu mikrobiyal patojenler yalnızca meyvenin kalitesini düşürmekle kalmaz, aynı zamanda tüketicilerde sağlıkları için ciddi sonuçlar doğuran gıda reaksiyonlarına da neden olabilir. Dolayısıyla, bu patojenlerin saldırısını kontrol altına almanın ve önlemenin önemi, meyveye büyümesinin farklı aşamalarında zarar verebilir.

2.3.Viral hastalıklar ve vektörler

Mavi yemiş bitkilerinde yaygın olarak görülen virüsler, Blueberry scorch virus (BlScV) — Carlavirus, Blueberry shock virus (BlShV) — Ilarvirus, Blueberry shoestring virus (BSSV) — Sobemovirus, Blueberry red ringspot virus (BRRV) — Soymovirus, Caulimoviridae (pararetrovirüs), Blueberry necrotic ring blotch virus (BNRBV) — Kitavirus, Blueberry leaf mottle virus (BLMoV) — Nepovirus. Blueberry mosaic-associated virus (BlMaV) — Ophiovirus, Mavi yemişte görülen halkalı leke Nepovirüsleri: Tobacco ringspot virus (TRSV) & Tomato ringspot virus (ToRSV) — Nepovirus olarak sıralanmaktadır. Ülkemizde 2025 yılında yapılan bir çalışma ile Karadeniz bölgesinde BlMaV ve BLMoV virüsleri rapor edilmiştir. Bu virüslerden Scorch (BlScV): Duyarlı çeşitlerde %80'e varan verim kaybı, Shoestring (BSSV) ise Enfekteli bitkilerde yaklaşık %25'e kadar verim kaybına neden olduğu bilinmektedir. Virüsler vektörler vasıtasıyla yayılım gösterirler örneğin; afitler (BlScV, BSSV), polinatörler/polen (BlShV), eriophyid akarlar (BNRBV), hançer nematodları (TRSV/ToRSV), aşı/çoğaltım (BRRV, BlMaV) ile yayılırlar. Ayrıca, sertifikasız ve hastalıklı çoğaltım materyali (fidan/çelik) kullanılmasında çoğu virüslerin yayılmasında önemlidir. Virüs hastalıkları ile mücadelede hastalıklı üretim materyalinin imhası ve vektörle savaş esastır.

3. Hasat Öncesi ve Sonrası Entegre Mücadele Yöntemleri

3.1.1. Kültürel Önlemler

Hava sirkülasyonunun artırılması: Bitkiler arası mesafe ve budama uygulamalarıyla nemli mikroiklim koşulları azaltılarak *B.cinera* ve *Colletotrichum* spp. gibi nem seven patojenlerin gelişimi sınırlandırılabilir. Bitkiler arası uygun mesafe bırakılması, yoğun sürgünlerin budanarak hava sirkülasyonunun artırılması ve yaprak dokusunun uzun süre nemli kalmasını önleme gibi uygulamalar, hem hastalık etmenlerinin başlangıç inokulumunu azaltmak hem de mikro-iklimi patojenler için daha az elverişli hâle getirmek açısından önemlidir. Çiçek/çiçeklenme sonrası kalan bitki kalıntılarının uzaklaştırılması, latent enfeksiyon kaynaklarının bastırılmasında etkilidir. Damlama sulama yaparak, yaprak yüzeyinin daha az

ıslanmasını sağlamak özellikle sporların su yardımıyla taşınmasını önlemeye yardımcı olur. Bu yaklaşım, özellikle nemin yüksek olduğu bölgelerde patojen baskısını azaltmada etkilidir.

3.1.2. Kimyasal Mücadele

Sentetik fungisitler (fenilpirazol, strobilurin grubu) hâlen birçok ülkede kullanılsa da, kalıntı sorunları ve direnç gelişimi nedeniyle kontrollü ve rotasyon esasına dayalı kullanım önerilmektedir. Geleneksel fungisit uygulamaları patojenlerde fungisit direnç gelişimi konusu ciddi bir sorun olarak literatürde yer almaktadır.

Mavi yemişteki gri küfü kontrol altına almak için benzimidazoller, dimetilimidazoller, triazoller, strobilurinler ve süksinat dehidrogenaz inhibitörleri (SDHI'ler) dahil olmak üzere çeşitli fungisitler kullanılmıştır. Her fungisit farklı mekanizmalar aracılığıyla etki eder (Shao ve ark., 2021). Örneğin, benzimidazol fungisitleri öncelikle patojenlerde mikrotübül proteinlerinin sentezini engelleyerek mitozlarını bozar ve böylece fungisidal etki gösterir (Oliveira ve ark., 2017). *B. cinerea*'nın manganez inhibitörleri ya da strobilurin grubu fungisitlere karşı direnç geliştirdiği bildirilmiştir (Saito ve ark., 2016). Gri küfü kontrol altına almak için aktif bileşenlerin geliştirilmesinde son zamanlarda ilerlemeler kaydedilmiştir. Benzovindiflupir gibi bazı yeni fungisitler, gri küfe karşı güçlü inhibitör aktivite göstermektedir (He ve ark.,2018). Potasyum bikarbonat, kalsiyum şelatlar ve sodyum silikat gibi tuz çözeltileri, fungus yapısını ve hücresel işlevleri değiştirerek *B. cinerea* üzerinde dikkate değer inhibitör etkiler göstermiştir (Youssef ve ark., 2019). *B. cinerea'*ya karşı belirgin aktiviteye sahip yeni bileşiklere ilişkin diğer raporlar arasında benzoylurea'nın belirli türevleri pirimidin, flavonoid ve 1,2,4-triazolo [4,3-c]triflorometilpirimidin yer almaktadır; bu moleküllerin daha fazla incelenmesi, gri küfe karşı yeni fungisitlerin geliştirilmesini sağlayabilir (An ve ark.,2023; Pan ve ark.,2024; Meng ve ark., 2024). Birden fazla fungisite karşı direncin ortaya çıkması, *B. cinerea'*da fungisit direncinin yaygınlığı artmaya devam ettikçe Mavi yemiş gri küfünün yönetimi için önemli bir zorluk oluşturmaktadır (Shao ve ark., 2021; Oliveira ve ark., 2017). Michigan'da yürütülen bir çalışmada, özellikle piraklostrobin ve difenokonazol için azalmış duyarlılık sıklıkları ile birlikte, birden fazla fungisite karşı artan bir direnç sıklığı bildirilmiştir (Baral ve ark., 2025). Benzer şekilde, Pasifik Kuzeybatısı'nda, *B. cinerea,* SDHI fungisitlerine karşı direnç geliştirmiştir ve belirli mutasyonlar çeşitli SDHI aktif bileşenlerine karşı çapraz dirençle sonuçlanmıştır (Abbey ve ark., 2024). Bu, direnci etkili bir şekilde yönetmek için dengeli fungisit kullanımı ve fungisit rotasyonu uygulanmalıdır.

Özellikle *B. cinerea* Gri küf yönetiminde hastalığın oluştuğu iklim ne çevre koşullarını belirlemek fungisit uygulamalarını azaltmak bakımından oldukça önemlidir. Şili'de yapılan bir çalışmada mavi yemişlerde gri küf kontrolü için geliştirilen bir modelin daha düşük gri küf görülme sıklığıyla sonuçlandığı bildirilmiştir. Çalışma, erken tahmin uyarı sisteminin (DSS) kullanılmasının eşit veya daha az fungisit kullanımıyla etkili gri küf kontrolü sağladığını göstermiştir (Van der Marwe ve ark., 2022). *B. cinerea* enfeksiyonunun erken ve en az zarar oluşumunu tespiti için hiperspektral görüntüleme (HSI) uygulamaları da araştırılmıştır. HSI ve kemometrik analizin entegrasyonu, depolama sırasında fungusla enfekte olmuş meyvelerin hızlı ve zararsız değerlendirilmesi için önemli bir potansiyel göstermiştir (Hanghbin ve ark., 2023).

Kimyasal mücadele, en eski ve en ucuz yöntemlerden biri olmasına rağmen, meyve kalitesi açısından iyi sonuçlar vermektedir. Bununla birlikte, çevre ve insan sağlığı açısından önemli sonuçları vardır.

3.1.3. Biyolojik Mücadele

Hasat öncesi uygulamalarda biyolojik ajanların kullanılması, latent enfeksiyonları önlemeye yardımcı olur; bu da hasadın kalitesini ve raf ömrünü olumlu yönde etkiler. *Trichoderma harzianum*, *Bacillus subtilis* ve *Pseudomonas fluorescens* gibi mikrobiyal ajanlar, bitki yüzeyinde rekabet ve antibiyotik üretimi yoluyla patojen gelişimini baskılamaktadır. Bazı mikrobiyal preparatlar, bitkide sistemik direnç (ISR) yanıtını da uyararak koruyucu etki sağlar. Mikrobiyal antagonistler, biyolojik mücadelede önemli bir yer tutar. *Trichoderma asperellum* TM11 izolatının, Mavi yemiş kök çürüklüğü etmeni üzerindeki etkisi detaylı olarak incelenmiş ve hastalık kontrolünde ümitvar bulunmuştur (Li ve ark.,2023). Gomes ve ark 2023 yılında yaptıkları çalışmada yerel mikrobiyal toplulukların karakterizasyonu da biyolojik mücadelenin etkinliğini artırmak açısından araştırıcılar ve Mavi yemiş rizosferinde *Trichoderma* sp. ve *Bacillus* sp. gibi faydalı mikroorganizmaların izole edildiği bildirilmişlerdir. Kurniawan ve ark. (2018), Mavi yemiş meyvelerinde, in vitro koşullarda *Bacillus* sp.ve *Pseudomonas* sp. kullanılmışlar, bakterilerin etki mekanizmasının bir parçası olarak antimikrobiyal özelliklere sahip peptit kökenli bileşikler ürettiğini ve *B. cinerea* ve *A. alternata* için sırasıyla %42 ve %27'lik değerlerle in vitro büyümesini engellediğini bildirmişlerdir.

Trichoderma sp. meyvelerde fungusların neden olduğu hastalıkları engelleme kapasitesi nedeniyle, Mavi yemişin hasat sonrası hastalıklarını kontrol eden en önemli antagonist tür olarak kabul edilir (Romero-Arenas ve ark., 2017). Ayrıca, antibiyotik üretmedikleri, toksik olmadıkları ve çevreyi kirletmedikleri *için Debaryomyces hansenii, Meyerozyma caribbica, Rhodotorula minuta* gibi mayaların etkisini inceleye araştırmacılar, ana etki mekanizmalarının antibiyotik olduğunu ve uçucu bileşiklerin üretimi ile direnç indüksiyonu olduğunu bilidirmişlerdir. Yapılan çalışmada izole edilen bakterilerin etki mekanizmasının bir parçası olarak antimikrobiyal özelliklere sahip peptit kökenli bileşikler ürettiğini ve *B. cinerea* ve *A. alternata* için sırasıyla %42 ve %27'lik değerlerle in vitro büyümesini engellediğini bildirmişlerdir (HernándezMontiel ve ark., 2018). *Bacillus* sp*, Streptomyces* sp*, Pseudomonas* spp. ve *Candida oleophila* dahil olmak üzere çeşitli mikroorganizmaların mahsullerde gri küfü kontrol ettiği bilinmektedir. Besin rekabeti, hifsel parazitizm, indüklenen sistemik direnç ve doğal antagonistik bileşikler yoluyla hasat sonrası gri küfün biyolojik kontrolünü sağlarlar (Wang ve ark., 2022). Özellikle, Mavi yemişten izole edilen *Bacillus siamensis* YJ15 suşunun, *B. cinerea* ve 11 diğer bitki patojenik fungusları etkili bir şekilde inhibe eden uçucu organik bileşikler (VOC'ler) ürettiği bulunmuştur.

3.2. Hasat Sonrası Uygulamalar

Mavi yemiş meyveleri, ince kabuk yapısı ve yüksek nem içeriği nedeniyle hasat sonrası dönemde hızla bozulabilmektedir. Bu nedenle patojen gelişimini engelleyici hasat sonrası yapılacak uygulamalar kritik önemdedir.

3.2.1. Soğuk Zincir Yönetimi

Hasat sonrası en hızlı uygulanabilen yöntemlerden biridir. Hızlı ön soğutma (0–4 °C), patojen gelişimi ve solunum hızını yavaşlatarak raf ömrünü artırır. Mavi yemiş meyvelerinde 0-4 °C sıcaklık ve yüksek bağıl nem (%90-95) koşullarının sağlanması, solunum hızını ve patojen gelişimini azaltmada etkilidir. Bir çalışmada kitosan, nano-kaplama uygulamasının soğuk depolama ile kombinasyonunda meyvede ağırlık kaybının %2.22 gibi düşük bir düzeyde kaldığı bildirilmiştir (Li ve ark., 2021).

3.2.2. Modifiye Atmosfer ve Kontrollü Atmosfer

Mavi yemişin hasat sonrası raf ömrünü uzatmak için kullanılan modifiye atmosfer ve kontrollü atmosferler teknolojileri, depolama ve taşıma sırasında gaz bileşiminin (O2 ve CO2) değiştirilmesine dayanmaktadır (Defilippi ve ark, 2017). Düşük O_2 (1–5%) ve yüksek CO_2 (10–20%) ortamında meyveler muhafaza edilerek spor gelişimi ve etilen üretimi baskılanabilir. *Colletotrichum* ve *Penicillium* gibi aerobik patojenlere karşı etkilidir. Düşük O_2 ve yüksek CO_2 içeren atmosferlerde, meyve solunumu baskılanır, etilen üretimi azalır ve aerobik patojenlerin gelişimi gecikir. Şu ana kadar bildirilenlere göre, hastalık kontrolünde rol oynayan Mavi yemiş meyvesinin fiziksel ve kimyasal özelliklerini koruma yöntemi olarak modifiye edilmiş ve kontrollü atmosferler kullanılmaktadır. Bununla birlikte, bu teknolojinin antimikrobiyal etkisini artırmak için UV radyasyonu, kükürt dioksit, 1-metilsiklopropen veya antioksidan aktiviteye sahip bileşikler gibi diğer yöntemlerle birleştirilmesi gerekmektedir (Chiabrando ve Giacalone, 2011; Follett ve Neven, 2020; Rodriguez ve Zoffoli, 2016).

UV Uygulamaları

UV C ışınlama ve ozon uygulamaları, yüzeydeki patojen sporlara doğrudan etki ederek çürüme başlangıcını geciktirebilir. Literatürde UV C uygulamalarının Mavi yemiş gibi küçük meyvelerde bakteri/mikrobiyal yükü düşürmede başarılı olduğuna dair bulgular yer almaktadır. Bu fiziksel uygulamalardan önce meyve yüzeyinin hasarsız ve temiz olması, etkinliğin artmasına katkı sağlar. Özellikle *B. cinerea* ve *Alternaria* sp. için etkili olduğu bilinmektedir. Ozon uygulamaları: Oksidatif stres yaratarak mikrobiyal hücre duvarını tahrip eder. Latorre ve ark., (2012), Mavi yemişden izole edilen *B. cinerea, C. cladosporioides ve C. herbarum* konidiyaları üzerindeki UV-A, UV-B ve UV-C radyasyonunu değerlendirerek orta ve kısa ışık kullanarak çok daha büyük bir etki elde edilebileceğini ve bu fungus türlerinin popülasyonunun azaltılabileceğini kanıtlamıştır. Öte yandan, diğer araştırmalar bu yeni teknolojinin hasat sonrası çürümeyi %10 oranında iyileştirebileceğini bildirmiştir (Nguyen ve ark., 2014). Son zamanlarda yapılan bir değerlendirme (Yang ve ark., 2019), hasat sonrası Mavi yemişe uygulanan UV-C radyasyonunun DPPH antioksidan kapasitesini ve süperoksit dismutazı kontrole kıyasla sırasıyla %33 ve %54 oranında artırdığını doğrulamaktadır. İşlem görmüş meyvelerdeki antosiyanin içeriği %23,7 artmıştır; bu, bitkinin savunmasında rol oynayan bir parametredir ve kalitesini daha uzun süre korur.

Kitosan, Bitki ekstrakları ve Uçucu Yağ Uygulamaları

Son yıllarda, patojen popülasyonunu azaltmak amacıyla yararlı mikroorganizmalar ve hasat sonrası dönemde patojenleri kontrol etmek için alternatif bir biyopolimer olan kitosan gibi diğer doğal kökenli bileşiklerin kullanılmasıyla biyolojik mücadele yöntemlerinin kullanımı artmıştır (Gutierrez-Martinez ve ark., 2018). Yüksek biyolojik değere sahip uçucu yağlar ve bitki extratları da sentetik fungisitler yerine hasat sonrası hastalıkların kontrolünde etkili bir alternatif olarak kabul edilmektedir.

Mavi yemiş meyvelerinde kitosan bazlı kaplamaların uygulandığı çalışmalarda, fiziksel bariyer oluşturarak, anti-mikrobiyal etki gösterdiği ve raf ömrünü uzattığı bilinmektedir. Li ve ark (2021), yaptıkları çalışmada nano-kitosan film uygulamasında yeşil / mavi renk kaybı, ağırlık kaybı ve mikrobiyal popülasyon artışının bastırıldığı bildirilmiştir. Çalışmalarda kitosan ile birlikte salisilik asit uygulamasının, *B. cinerea*'ya karşı etkili olduğu gösterilmiştir. Vieira ve ark. (2016), kitosanın Mavi yemiş meyvelerinin kaplaması için aloe vera ile birlikte kitosanı kullanmışlar ve *B. cinerea* büyümesinde yaklaşık %50 oranında bir azalma, su kaybında azalma ve fenolik bileşik içeriğinde artış elde etmişlerdir. Kitosanın diğer bileşiklerle birlikte kullanımı inceleyen Yang ve ark., (2014) Mavi yemiş yapraklarından elde edilen biyolojik

değere sahip bir özütü kitosan ile karıştırarak kullanmışlar ve bu kombinasyonun meyvelerin hasat sonrası raf ömrünü 2 °C ve %95 bağıl nemde 35 gün uzatmaktığını bildirmişlerdir. Yang ve ark. (2014), Mavi yemiş yaprak özütlerini *Staphylococcus aureus, Listeria monocytogenes, Salmonella typhimurium* ve *Escherichia coli* üzerinde 25 g/L'lik minimum inhibitör konsantrasyonu ile 7,5 mm'den büyük bir inhibisyon elde etmişlerdir.

Bitki özleri kullanarak mavi yemişte gri küfünün biyolojik kontrolünde araştırmalar, ayçiçeği başağı özlerinde bulunan diterpenoid bileşiklerinin *B. cinerea*'ya karşı belirgin antifungal özelliklere sahip olduğunu ve belirli bileşiklerin önemli inhibitör etkiler gösterdiğini göstermektedir. Ayçiçeği başağı özlerinden elde edilen etil asetat özütü, 1,6 mg/mL konsantrasyonda test edilen Mavi yemiş meyvelerinin %42,9'unu *B. cinerea* enfeksiyonundan korumuş ve bu da meyvelerde hasat sonrası hastalıkların hafifletilmesinde biyolojik bir kontrol olarak potansiyelini göstermektedir (Santoro ve ark., 2018).

Sonuç

Mavi yemiş (*Vaccinium corymbosum*), yüksek antioksidan kapasitesi ve kronik hastalıkların önlenmesine katkı potansiyeli nedeniyle yoğun talep gören bir meyvedir. Bununla birlikte, çeşitli fitopatojenlere karşı belirgin duyarlılık göstermesi, ticari değerin korunması için etkili hastalık yönetimi stratejilerini zorunlu kılar. Hasat sonrası kalite ve raf ömrünün sürdürülebilmesi amacıyla, patojen kaynaklı bozulmaların kontrolüne yönelik alternatif yaklaşımların araştırılması güncelliğini korumaktadır. Mavi yemiş yetiştiriciliğinde hastalık yönetiminde birincil yaklaşım kültürel önlemlerdir. Bu kapsamda, plantasyonlarda optimum hava akışı ve ışık koşullarının sağlanması, hastalıklı bitki artıklarının hızla uzaklaştırılması ve inokulum kaynaklarının azaltılması esastır. Ayrıca, uygun budama ve bitki yoğunluğunun düzenlenmesiyle kanopi içinde nemin düşürülmesi, gri küf gelişimi için elverişsiz bir mikroklima oluşturur (He ve ark.,2018).

Kimyasal ve biyolojik kontrol stratejilerinin rasyonel entegrasyonu, üretim sistemlerinde yaygın biçimde benimsenmektedir. Sürdürülebilir yönetim yaklaşımları ise uzun vadeli ve çevre dostu ilkeleri benimsenerek kimyasal girdilere bağımlılığı azaltmayı hedefler. Özellikle Mavi yemişte en fazla ekonomik zarar yapan patojen olan *B. cinerea* karşı yüksek düzeyde dayanıklılık gösteren çeşitlerin seçimi ve ıslahı, hastalığın görülme sıklığını kökten azaltabilecek temel stratejidir. Dayanıklılık genlerinin belirlenmesi için yabani Mavi yemiş genetik kaynaklarının taranması ve bu genlerin melez ıslah teknikleriyle kültüre alınmış çeşitlere aktarılması bu sürecin en önemli adımlarıdır.

Entegre Zararlı Yönetimi, farklı etki mekanizmalarına sahip kontrol metotlarını uyumlu ve uygulanabilir bir yönetim çerçevesinde bir araya getirmek önemli bir mücadele şeklidir. Yetiştirme sezonu boyunca, fenolojik gelişme dönemleri, iklim ve çevre koşulları izlenmeli, kültürel önlem, biyolojik kontrol ajanlarının kullanımı ve gerektiğinde seçici fungisit uygulamaları stratejik olarak uygulanmalıdır. Hasat sonrası dönemde *B. cinerea* 'nın baskılanması için uygun kimyasal seçenekler mevcuttur; ancak bu uygulamalar, kalıntı limitleri ve ticari raf ömrü hedefleri gözetilerek, biyoteknik ve fiziksel yöntemlerle birlikte değerlendirilmelidir. Tüm bu yaklaşımların etkinliğini artırmak üzere tahmin-uyarı sistemlerinin geliştirilmesi ve uygulanması oldukça önemlidir. Tahmin- erken uyarı sistemleri iklim verileri ve hastalık gelişim modellerini kullanarak karar verme süreçlerini destekler ve gereksiz fungisit uygulamalarını en aza indirir.

Bu derleme, mavi yemişin hasat öncesi ve sonrası hastalıkların önlenmesine yönelik uygulanabilir alternatif mücadele yöntemlerine ve bunların etki mekanizmalarına odaklanarak, gelecekteki araştırmalar için yol gösterici ilkeler sunmayı amaçlamaktadır.

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SPATIO-TEMPORAL DYNAMICS OF URBAN EXPANSION IN A NORTHERN DISTRICT OF BANGLADESH USING VIIRS NIGHT-TIME LIGHTS AND MODIS LAND COVER IN GOOGLE EARTH ENGINE

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ABSTRACT

Monitoring urban expansion in secondary cities is essential for understanding regional development patterns and guiding sustainable planning. Using VIIRS Night-Time Light (NTL) annual composites and MODIS land cover (MCD12Q1) data within the Google Earth Engine (GEE) environment, this study explores the spatio-temporal pattern of urban growth in Rangpur District, Bangladesh for the period 2013-2022. MODIS Level-1 land-cover classifications were combined with annual NTL radiance to exclude urban (Class 13) and agriculture (Classes 10, 12, 14) and calculate sum of lights (SOL) for each class. For the SOL analysis, radiance increases without exceptions in both habitat and agricultural categories. Urban SOL rose from 356.90 nW/cm²/sr in 2013 to 603.72 nW/cm²/sr in 2022, supporting increasingly luminous built-up activity. A steep rise was also observed in agricultural zones (from 4,350.43 nW/cm²/sr in 2013 to 9,078.00 nW/cm²/sr in 2022), reflecting the spread of peri-ran growth and perhaps farmland-to-urban land use change. In the study period, total district-wide SOL increased from 4,889.33 to 10,006.91 nW/cm²/sr ($p < 0.01$). Socially the four representative years (2013, 2016, 2019, 2022) illustrate evident radiance intensification surrounding Rangpur city, major corridors, and upcoming urban centers. The research shows that combining NTL and LULC data offers an affordable, high-resolution and near-continuous framework for tracking urbanisation, particularly where field-based measurements are constrained. This demonstrates the fully GEE-based workflow that offers fast processing and reproducibility of urbanization assessments in Bangladesh and other developing areas.

Keywords: Night-Time Light, Urban Expansion, VIIRS, MODIS, Google Earth Engine, Land-Use Change, SOL Analysis.

1. INTRODUCTION

Urbanization is the most truly transformative phenomena of the twenty-first century. Cities are undergoing rapid growth across the globe, transforming their built environments, affecting their surrounding biophysical and socio-ecological systems (Seto et al., 2012). Although megacities are often the most highlights, secondary cities–medium-size urban hubs that link rural and metropolitan areas–have key impacts on development paths (UN-Habitat, 2020). These cities are undergoing unprecedented but poorly documented change due to rising mobility, commercial activity, electrification, and migration in the developing world. Bangladesh reflects this trend. While a considerable body of literature exists on the Dhaka urban agglomeration, secondary cities, including Rangpur, are becoming significant in terms of effective regional planning, dispersing economic activity away from the capital as well as achieving balanced national development (Islam & Adnan, 2020). The utilization of remote sensing has made a new horizon for monitoring urban change more efficiently. Of all satellite-based tools, Night-Time Light (NTL) imagery has emerged as a critical proxy for human activities, economic growth, electrification and urban sprawl (Li et al., 2020). Compared with the historical DMSP-OLS system, the VIIRS Day/Night Band (DNB) provides enhanced radiometric sensitivity, less saturation, and greater temporal stability, allowing it to be well-suited for examining urban expansion in medium-sized cities (Elvidge et al., 2017; Ghosh et al., 2013). NTL has limitations owing to its lower spatial resolution, but when combined with the MODIS MCD12Q1 products, which provide up-to-date global land-use classifications every year, NTL may be used for improved spatial interpretation and stronger links between radiance intensification in the NTL and land-use classes (Herold et al., 2018; Zhang et al., 2021).

The combination of NTL and land-cover data has been especially effective in identifying peri-urban growth. Several studies in Asia and Africa have shown the gradual increase in radiance in the agricultural areas typically align with urban growth as well as informal settlements or developing business corridors over time (Pandey et al.2019, 2022; Deval & Das, 2021). Although there is an increasing level of remote sensing application over Bangladesh, continued integrated assessments of secondary cities are much limited in the long run. Despite Rangpur District as an important new administrative and commercial centre of northern Bangladesh being a subject of great infrastructural and socio-economic change in the last decade, little analytical attention has been given to the urban dynamics of the area in the academic literature. This study helps to fill that gap by studying spatio-temporal urban growth in Rangpur from 2013 to 2022 using a VIIRS–MODIS fusion methodology performed on Google Earth Engine. The trinity of NTL time series- land-use change-dynamics of urban growth The aim is to quantify strength and direction of urban brightness change, evaluate spatial footprint of peri-urban land-transformation and extent of NTL–LULC-coupled data for appraising urban process in medium-sized cities. By producing annual statistics and spatial maps for key years, this study provides an evidence-based account of the changing extent of Rangpur's urban footprint and demonstrates the methodological potential of broader applications in Bangladesh and similar developing regions.

2. STUDY AREA

Rangpur District located in northern Bangladesh is one of the important administrative, commercial and educational centers of Rangpur Division (Figure 1). It is located at 25.20°–25.80° N latitude and 89.00°–89.50° E longitude and covers an area of about 2,307 km² (Banglapedia, 2023; BBS, 2022). The landforms in the area consist of agricultural areas, villages, urban neighborhoods, corridors of transportation, and a quickly developing commercial area. Rangpur city serves as the main urban center with characteristics of peri-

urban growth along some key highways and pastoral developments within the alluvial plains of the Teesta Basin are dominant factors to agricultural and settlement practices (Hossain & Rahman, 2020). More than 3 million people live in Rangpur, which offers an active rural–urban interface in an urban growth hotspot, making it a perfect place to study land-use change over time.

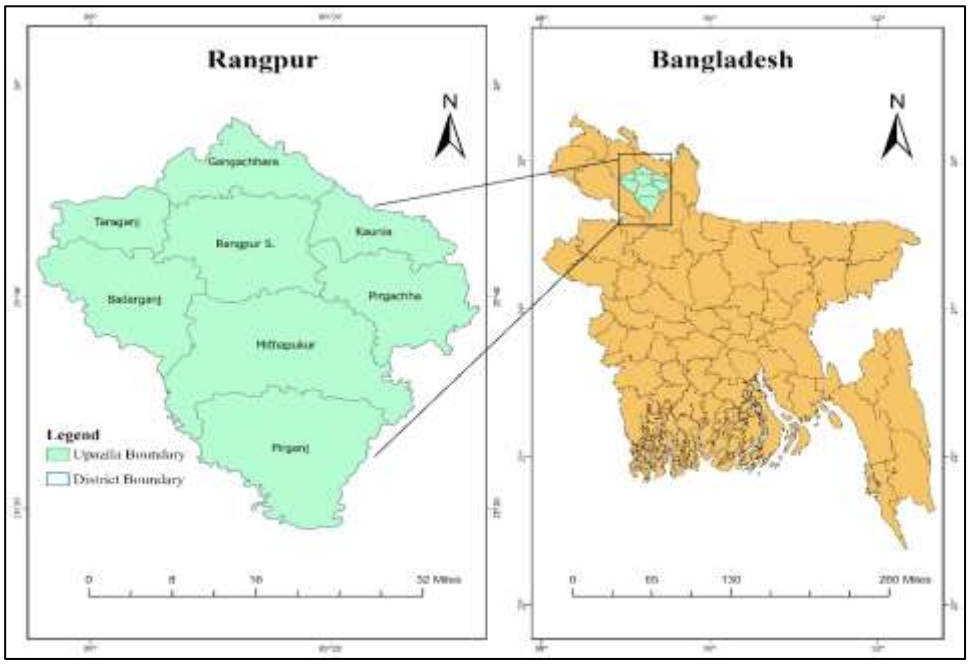

Figure 1: Map of the study region

3. DATA AND METHODOLOGY

The present study was based on two large geospatial datasets that were processed on the Google Earth Engine. Annual NTL composites (V21 and V22) from VIIRS were assembled for the years 2013–2022. This method effectively eliminates temporary lights including fire and short-lived events, yielding more accurate radiance values (Miller et al., 2020). For an annual land-cover classification, MODIS MCD12Q1 land-cover dataset was applied for distinguishing urban (Class 13) and agricultural (Classes 10, 12, 14) areas.

Urban and Agricultural masks for the years were generated as well as a mask to pinpoint areas that may be converting from agriculture to urban use. To quantify brightness associated with each land-use category, we applied the masked SOL methodology which sums all radiance values in the study area (Zhao et al., 2020). This methodology has been useful to identify the urban sprawl dynamics, economic growth and the urban expansion (Shi et al., 2014).

Spatial visualization of four representative years (2013, 2016, 2019 and 2022) were selected with the aim of capturing the early, mid and late phases of urban development. The GEE workflow provided the advantages of computational efficiency, reproducibility and scalability. These outputs consist of a ten year SOL dataset and spatial interpretation in the form of four combined radiance maps. Figure 2 represents the main methodological procedure of the study.

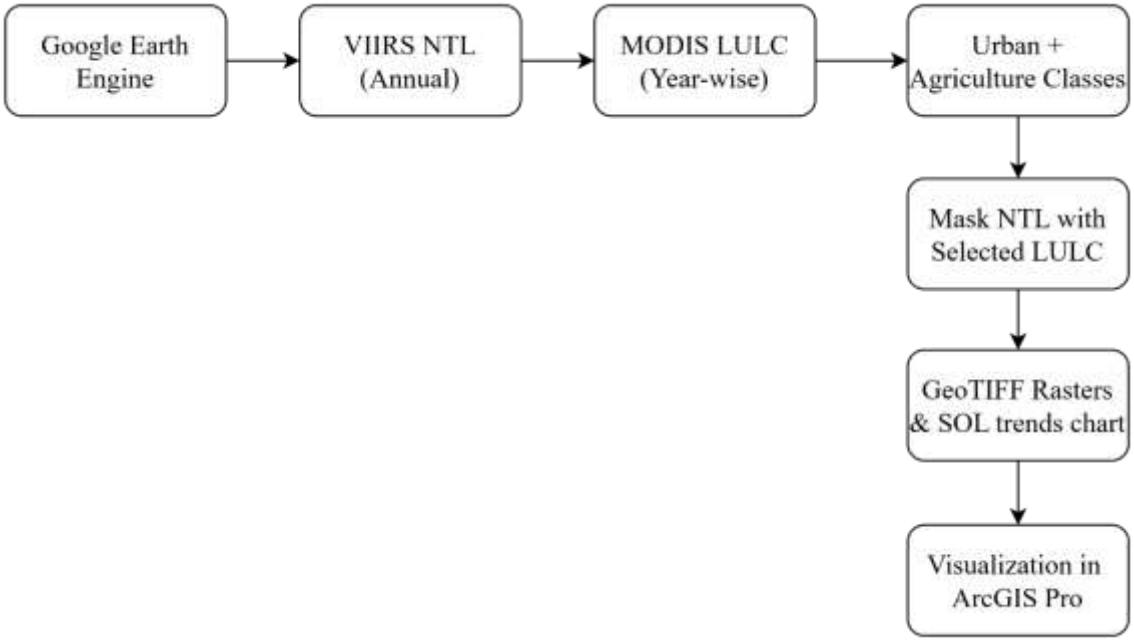

Figure 2: Flowchart of the overall methodology

4. RESULTS

The SOL analysis shows an increasing tendency of brightness in Rangpur District during the ten years (Figure 3). Urban SOL growth was consistent in nature, which is indicative of the progressive aggregation of built-up infrastructure, commercial facilities and electrified households. Radiance originally high only in densified areas, with agricultural places showing up in peri-urban parts near the city, gradually getting brighter. Such pattern reveals a sequential change in land use from agriculture to mixed farm with development of human settlements, spurred by population increase, economic diversification and improvement in transport.

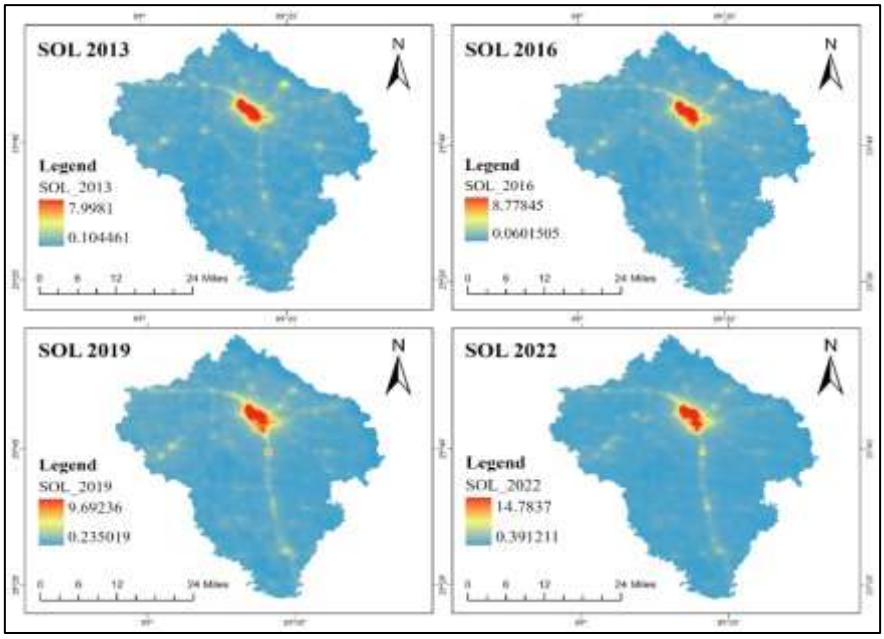

Figure 3: Spatial distribution of combined radiance (SOL) in Rangpur District for 2013, 2016, 2019, and 2022.

The spatial maps demonstrate the phase of greater illumination. The map for 2013 shows a concentrated bright area around the core of the Rangpur city and faintness along the main roads. In 2016, brightness extended outwards, especially to the south and southwest of the explosion. This indicates significant peri-urbanization, while the medium-intensity illumination observed in the 2019 map shows that medium-intensity illumination is able to grasp wide areas. The urban sprawl is greatly augmented and shines brighter, signifying continued economic activity and urbanization if another 2022 year of mega data is to be assumed. This spatial agreement between radiance intensification and the known development corridors supports the usefulness of NTL data to monitor urban growth.

5. DISCUSSION

The SOL of Rangpur in the spatiotemporal analysis displays a gradual increase in focus of nighttime light radiation between 2013 and 2022 particularly for 2013, 2014 and 2022, suggesting a rapid social-economic transition for the area (Table 1). Recently documented similar associations between increasing night-time radiance and urban expansion in regions of India, Pakistan and Nepal have shown that high radiance growth corresponded with economic expansion and infrastructure development (Pandey et al., 2022; Small et al., 2018). SOL maps indicate the relative persistence of the urban core as the most dominant illumination hotspot over the course of the study period but progressively enlarged lighted areas correspond to urban expansion and increased human activity in outer urban areas. A distinct transition observable from a dim core in 2013, to a much more luminous and spatially broad feature by 2022.

Table 1: Change of sum of lights (SOL) for urban, agricultural, and total areas

Year	Urban SOL (nW/cm²/sr)	Agriculture SOL (nW/cm²/sr)	Total SOL (nW/cm²/sr)
2013	356.895	4,350.43	4,889.33
2016	383.24	4,388.22	4,960.78
2019	407.673	7,166.47	7,696.20
2022	603.715	9,078.00	10,006.91

A SOL aggregation chart further supports these observations with the quantification of Urban SOL, Agriculture SOL, and Total SOL (Figure 4). The total SOL goes from about 4,800 units in 2013 to almost 10,000 units in 2022, meaning the increase over the decade is more than twice. Rapid agriculture and urbanization are accelerating this trend. Remarkably, Agriculture SOL has remained the largest single component, implying considerable growth in electrification and nighttime agricultural operations, especially pumping irrigation, crop processing, and rural infrastructure development. These results are also consistent with more general processes of peri-urbanisation in secondary cities in South Asia, as the rural–urban interface fades in the context of emerging settlements, markets and transport corridors (Sahana & Patel, 2019).

However, Urban SOL, which is also much lower in order of magnitude, steadily rises between 2013-2022. A more substantial increase is noticeable after 2019, consistent with the spatial spread seen in the maps. This implies densification of urban form, increase in economic activities, and new settlements are being constructed at the urban periphery level. The very prominent linear features seen in 2019 and 2022 maps also coincide with transport corridors

further highlighting the significance of road-led development nature of the urban growth of Rangpur.

By looking at the spatial maps separately and the aggregated values separately you can see that while the urban core becomes brighter, the agricultural landscapes are the most brightest and have the most noticeable overall change coming from them as it is the most bright area and is taking hold on to total illumination as they become increasingly bright. This pattern indicates a hybrid growth model with urbanization as well as rural modernization as the contributors to energy consumption and nighttime lights.

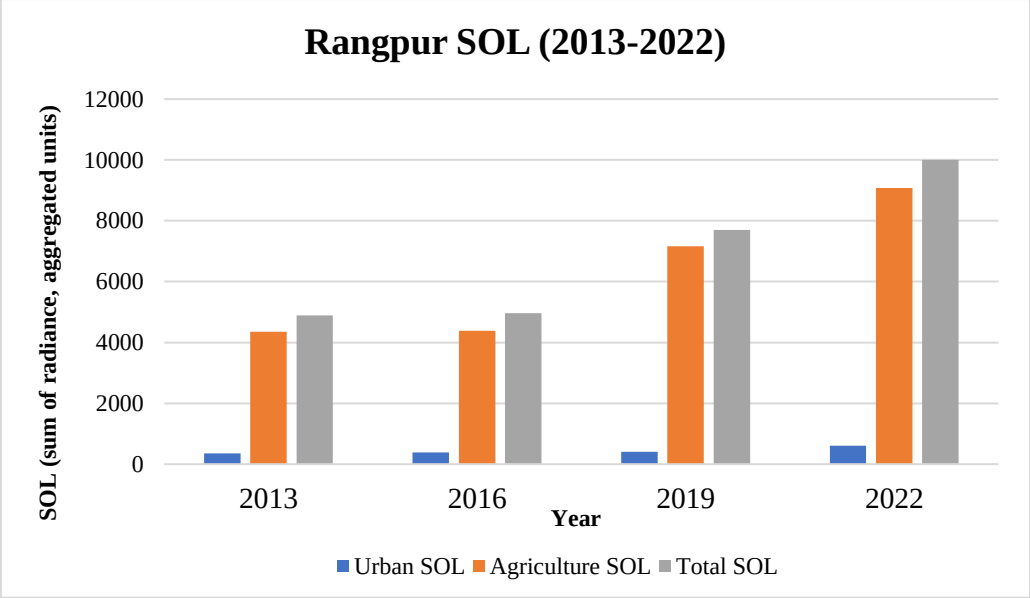

Figure 4: Temporal trend of sum of lights (SOL) for urban, agricultural, and total areas in Rangpur District (2013–2022).

Combining VIIRS NTL and MODIS LULC data was very useful for characterizing radiance change drivers. Although VIIRS by itself picks up where MODIS leaves off in terms of brightness, it does not distinguish land types, and so the MODIS classification clarifies if urban, agriculture, or some other land type is responsible for illumination trends. The ability to return multi-year processed results without local computational restraints was significantly improved through the use of Google Earth Engine (GEE) (Gorelick et al., 2017).

From the perspectives of environmental and planning, the increase of SOL may reflect the higher demand for energy, the elevated artificial light spreading, even the effect on heat island effect and disturbance of ecology. Previous studies conducted in South Asia have shown how NTL-based tracking provides a feasible, cost-effective solution to spatially inform unplanned urban sprawl vulnerability and can serve as a complementary input for formulating evidence-based growth-management measures (Pandey et al., 2022; Sahana & Patel, 2019). Hence, SOL can be a strong candidate for monitoring land development pressure, rural transformation and sustainability challenges in fast changing region such as Rangpur.

In summary, the integrated SOL evidence from map-based and aggregated data indicates that between 2013 and 2022, Rangpur has undergone significant urban and agricultural growth, characterized by the enlarging size of lighted regions, increasing total radiance, along with a close coupling between rapid expansion of built-up area and economic activities.

6. CONCLUSION

The results of this study represent a first-ever fully integrated spatio-temporal assessment at high resolution of urban growth in Rangpur District from 2013 to 2022. It shows considerable increases in nocturnal brightness, indicative of regional urbanisation and continuing changes over peri-urban agricultural land. It sheds light on regional socio-economic progress and better infrastructure: The increasing illuminated footprint. The method is inexpensive, scalable and ideal for the developing world, where urban-survey data are sparse. In future works, other socio-economic indicators, road-network data or even machine learning methods can be used in conjunction with our models to improve the prediction of urban-growth and to further understand urbanization processes.

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HAVACILIKTA OTONOM BAKIM VE ONARIM İÇİN KENDİNİ İYİLEŞTİREN MALZEMELER

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ÖZET

Havacılıkta kullanılan malzemeler; yüksek sıcaklık, basınç değişimleri, aerodinamik yükler, darbe ve yorulma etkileri nedeniyle sürekli bir hasar riski altındadır. Bu koşullar, uçak yapılarında zamanla mikro çatlakların veya yüzey bozulmalarının oluşmasına yol açmaktadır. Bu nedenle bakım ve onarım süreçleri, uçuş güvenliğini sağlamak açısından kritik bir role sahiptir. Ancak geleneksel bakım yöntemleri, yüksek maliyetli olmaları, uzun işlem süreleri gerektirmeleri ve insan hatalarına açık olmaları nedeniyle istenen verimliliği her zaman sağlayamamaktadır. Kendini iyileştiren malzemeler, hasarı dış bir müdahaleye ihtiyaç duymadan otonom şekilde onarma yeteneği sunarak bu sınırlılıkları önemli ölçüde azaltmaktadır. Mikro çatlakları kendi içinde iyileştirebilme, kullanım ömrünü uzatma ve bakım ihtiyacını azaltma gibi avantajlar, bu malzemeleri havacılık yapıları için oldukça cazip hale getirmektedir. Ayrıca daha az malzeme kullanımı ve daha uzun servis ömrü sayesinde çevresel sürdürülebilirliğe de katkı sağlamaktadır. Bu çalışmada, kendini iyileştiren malzemelerin otonom bakım-onarım sistemlerine entegrasyonu incelenmektedir. Literatürde yer alan polimer, seramik ve metalik malzemelerde kullanılan farklı onarım mekanizmaları karşılaştırmalı olarak değerlendirilmiştir. Özellikle mikro kapsül ve mikro damar sistemleri, tersinir kimyasal bağlar ve şekil hafızalı alaşımlar, otonom iyileşme mekanizmalarının temelini oluşturan başlıca yöntemlerdir. Her mekanizmanın yapısal bütünlük, onarım hızı, tekrar

kullanılabilirlik ve malzeme uyumluluğu açısından farklı avantajları bulunmaktadır. Elde edilen değerlendirmeler, kendini iyileştiren malzemelerin havacılık sektöründe önemli bir potansiyele sahip olduğunu göstermektedir. Mevcut teknik zorluklara rağmen bu malzemelerin, gelecekte bakım süreçlerini otonom hale getirerek daha güvenilir, hafif ve uzun ömürlü havacılık yapılarının geliştirilmesine katkı sağlaması beklenmektedir.

Anahtar Kelimeler: Otonom bakım-onarım, kendini iyileştiren malzemeler, mikro kapsül sistemleri, şekil hafızalı alaşımlar, havacılık.

SELF-HEALING MATERIALS FOR AUTONOMOUS MAINTENANCE AND REPAIR IN AEROSPACE

ABSTRACT

Aerospace materials operate under harsh environmental and mechanical conditions, such as high temperatures, pressure fluctuations, aerodynamic loads, impact, and fatigue loading. These factors cause continuous risks of micro-crack formation and structural degradation in aircraft components. Therefore, maintenance and repair activities are essential for ensuring flight safety. However, traditional maintenance methods have major drawbacks, including high cost, long processing times, and susceptibility to human error. Self-healing materials offer a promising solution by enabling autonomous repair of damage without external intervention. Their ability to heal micro-cracks extends service life, and reduce maintenance demands, hence, making self-healing materials highly attractive for aerospace applications. Additionally, by minimizing material waste and increasing component durability, these materials contribute to environmental sustainability. This study examines the integration of self-healing materials into autonomous maintenance and repair systems for aviation structures. Various healing mechanisms reported in the literature are evaluated comparatively across polymeric, ceramic, and metallic material classes. Among these mechanisms, microcapsule- and microvascular-based systems, reversible chemical bonds, and shape memory alloys stand out as prominent self-healing strategies. Each mechanism offers different advantages in terms of structural compatibility, healing speed, reusability, and applicability to aerospace components. The overall assessment indicates that self-healing materials have strong potential for transforming maintenance operations in the aviation sector. Despite existing technical challenges, such as integration with composite structures, long-term reliability, and environmental stability, current research trends show that these materials may play a key role in developing safer, lighter, and more durable aerospace systems.

Keywords: Autonomous maintenance, self-healing materials, microcapsule systems, shape memory alloys, aerospace.

1.GİRİŞ

Endüstride kullanılan malzemelerin bakım onarım süreçleri, insan müdahalesi dahilinde periyodik muayeneler ile yapılmaktadır. Geleneksel yöntemler uzun yıllardır kullanılmasına rağmen aslında hem zaman hem de maliyet açısından sınırlamalar içermektedir. Özellikle zorlu koşullara maruz kalınan ve yüksek güvenlik gerektiren sektörlerde malzemelerin bakım ve onarım süreçleri aksamalara yol açabilmektedir.

Bu bağlamda kendini iyileştirebilen malzemeler geleneksel yöntemlerin ötesine geçebilecek yenilikçi bir çözüm önerisi sunmaktadır. Bu yaklaşım, havacılık gibi yüksek güvenlik standartları gerektiren sektörler de dahil olmak üzere geniş uygulama alanlarına uyarlanabilir olup büyük bir potansiyel taşımaktadır. Bu çalışma geleneksel yöntemlere alternatif olarak kendini iyileştiren malzemelerin yenilikçi olanaklarını ve özellikle havacılık alanındaki potansiyel rolünü incelemeyi amaçlamaktadır.

1.1. Havacılık Malzemelerindeki Hasar Riskleri ve Geleneksel Bakım Sınırlamaları

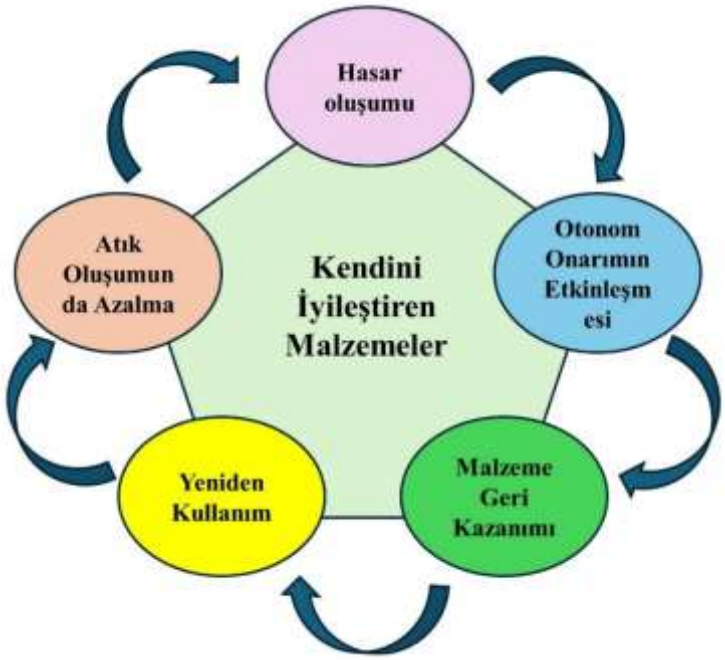
Hava araçları görevleri boyunca çeşitli çevresel etkiler altında çalışırlar. Zaman içinde yapısal bileşenlerde belirli düzeyde deformasyon oluşumu kaçınılmaz hale gelir. Maruz kaldıkları UV ışınları, tekrarlı basınç çevrimleri, nem ve sürekli sıcaklık değişimleri gibi faktörler hava araçlarında korozyon, delaminasyon ve mikro çatlaklar gibi yapısal hasar risklerine neden olabilmektedir. Bu nedenle kullanılan malzemeler ve bu malzemelerin bakım onarım süreçleri, zorlu çevresel koşullar nedeniyle büyük önem taşımaktadır. Hasar risklerine karşı sürekli bakım onarım faaliyetleri uçuş güvenliği açısından oldukça önemlidir. Bu süreçler havacılığın en kritik faaliyetlerinden olup havayoluna ait gider maliyetinin yaklaşık olarak %11'ini oluşturmaktadır (Verhagen et al., 2023). Geleneksel bakım süreçleri, hasarların erken tespiti için yetersiz kalabilmekte, bunda insan hatası da önemli bir paya sahip olmaktadır. Periyodik bakımlarda tespit edilemeyen hasarlar beklenmeyen arızalara sebep olabilir. Ayrıca geleneksel bakım süreçleri boyunca hava aracının yerde tutulması gerektiği için operasyonel süreklilik sekteye uğramaktadır.

1.2. Kendini İyileştiren Malzemelerin Rolü

Geleneksel bakım onarım yöntemlerinin yaygınlığını azaltabilecek, kendini onarabilen akıllı malzemeler mevcut sınırlamalar karşısında önemli bir çözüm potansiyeline sahiptir. Bu malzemeler, yaklaşık son 15 yılda artan performans gereksinimleri ve gelişen teknoloji sayesinde daha yaygın bir seçenek haline gelmiştir. Özellikle bakım ihtiyacının giderilmesinin zorlu olacağı uzay ortamları için gelecek vaadetmektedir (Pernigoni et al., 2021). Kendini iyileştiren malzemelerin havacılıkta bakım onarıma sunduğu avantajlar başlıca şu şekilde sıralanabilir:

- İnsan hatalarına karşı operasyonel verimliliği artırarak uçuş güvenliğinin sağlanması,
- Bakım sıklığının azaltılması ve böylece maliyetin düşmesi,
- İyileşmenin otonom olarak gerçekleşmesi sayesinde onarım giderlerinin düşmesi,
- Arıza oluşumundan önce onarım sayesinde uzun ömürlü yapıların geliştirilmesi, böylece atık oluşumunu en aza indirerek sürdürülebilirliğe katkı sağlaması.

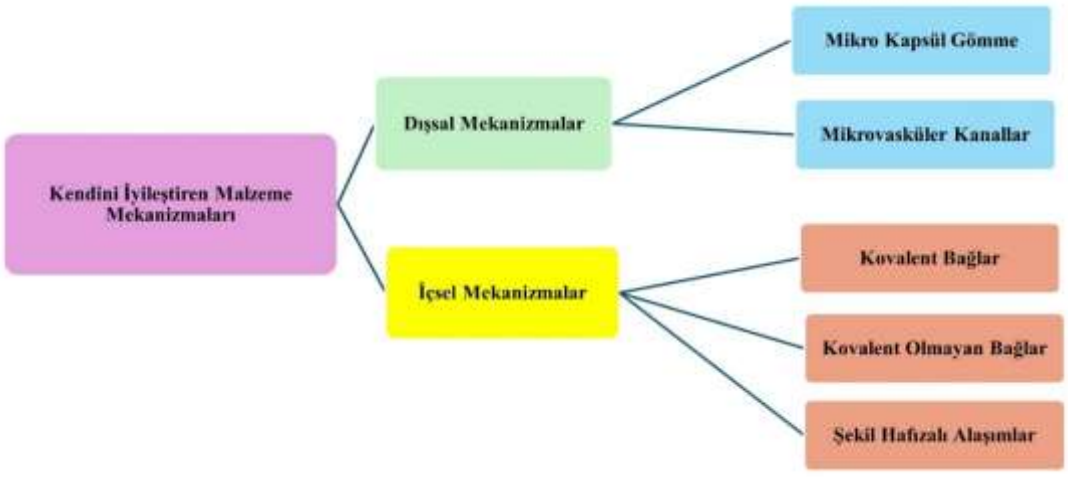
Şekil 1'de kendini iyileştiren malzemelerin döngüsel süreci gösterilmektedir. Bu döngü hasar oluşumunun otonom onarımı etkinleştirmesini ve böylece malzeme geri kazanımının gerçekleşmesiyle atık oluşumunda azalma sağlandığını vurgulamaktadır.



Şekil 1. Kendini onaran malzemelerde otonom onarım döngüsünün şematik gösterimi

2. KENDİNİ İYİLEŞTİREN MALZEMELERİN SINIFLANDIRILMASI VE İYİLEŞME MEKANİZMALARI

Kendini iyileştirme mekanizmaları farklı malzeme türlerinde benzer prensiplere dayalı olarak gerçekleşir. Bu mekanizma çeşitlerini dışsal ve içsel onarım olarak iki başlık altında incelemek mümkündür. Dışsal onarım mekanizmaları malzeme içine gömülmüş halde bulunan bileşenlere dayanarak onarım gerçekleştiren, kendiliğinden onarım yeteneğine sahip olmayan mekanizmalardır. İçsel onarm ise kimyasal bağlar ve fiziksel etkileşimler ile dışarıdan eklenmiş bir bileşene ihtiyaç duymadan çalışan iyileşme mekanizmalarıdır (Paul et al., 2025). Sınıflandırma birçok farklı başlık ile yapılabilir. Bu çalışmada bahsedilecek mekanizmalar için genel çerçeve Şekil 2'de gösterilmiştir.



Şekil 2. Kendini İyileştiren Malzeme Mekanizmalarının Sınıflandırılması

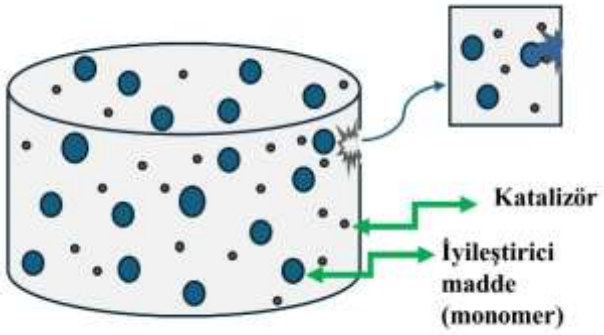
Malzeme türüne ve özelliklerine göre kullanılan mekanizma çeşitleri Tablo1'de gösterilmiştir. Tabloda polimer, seramik ve metal malzemelerin hangi yöntemler ile uyumlu olduğu ve bahsedilen mekanizmaların hangi sıklık derecesinde kullanıldığı görülebilir.

Tablo 1. Malzeme türlerine göre kullanılan mekanizma çeşitleri [Hücrelerdeki X işareti sayısı ilgili mekanizmanın malzeme sınıfında kullanım sıklığını göstermektedir. XXX: yaygın, X: daha az yaygın, Boşluk: kullanımı neredeyse bulunmamakta]

Malzeme Türü/ Mekanizma	Polimer & Kompozit	Seramik	Metal
Kapsülleme	XXX	XXX	X
Kanal Taşımacılığı	XXX	XXX	X
Tersinir Çapraz Bağlar	XXX		
Şekil Hafızalı Alaşımlar	X		XXX

2.1. Polimerik Malzemelerde İyileşme Mekanizmaları ve Uygulama Potansiyelleri

Polimer matrisli kompozit (PMC) malzemeler kolay işlenebilirlik, düşük ağırlık ve yüksek dayanım özelliklerinden ötürü en çok tercih edilen kompozit yapılar arasında yer alır. Ancak zorlu koşullarda hasara karşı hassas olmaları onları riskli kılar (Danaci, 2023; Paladugu et al., 2022). Şekil 3'te gösterildiği üzere polimerlerde mikro kapsül gömme mekanizmasında iyileşme süreci çatlak oluşumu ile başlar. Oluşan çatlak ilerledikçe malzemenin içine gömülmüş halde bulunan mikrokapsülleri kırarak iyileştirici maddenin serbest kalmasını sağlar. Serbest kalan iyileştirici madde çatlak boyunca ilerleyip katalizör ile birleşerek katılaşır ve böylece otonom iyileşme süreci tamamlanır. Bu mekanizmanın en büyük dezavantajı ise iyileşmenin yalnızca bir kere gerçekleşebilecek olmasıdır.



Şekil 3. Mikro kapsül gömme mekanizması

Takviyeli kompozit malzemeler, matris ve kompozit fazlarının birleşimi ile oluşan gelişmiş mühendislik malzemeleridir(Erden et al., 2023). Lif takviyeli epoksi kompozitlerin havacılık uygulamalarındaki kullanımı çok yaygındır. Boeing 787 Dreamliner'ın birincil yapısal bileşenlerinde %50'nin üstünde bir oranda karbonfiber takviyeli kompozit kullanımı bu malzeme grubunun sektör açısından en önemli örneğidir (Danaci, 2023; Zhang et al., 2023). Havacılıkta kullanılan kendini iyileştiren polimer kompozitler ile yapılan çalışmalarda, sıkıştırma ve darbe testlerinden sonra iyileşme oranının %92 ve %97 oranında olduğu

belirtilmiştir (Paladugu et al., 2022).Bu oranlar malzemenin oldukça yüksek iyileşme yeteneği kazanabildiğini ve kritik alanlarda kullanımı açısından yüksek potansiyele sahip olduğunun göstergesidir.

Havacılık sınıfı fiber takviyeli polimer kompozitlerde mikrovasküler kanal yapısına dayanan mekanizma ile yapılan çalışmalardan biri, havacılıkta otonom bakım uygulamalarının kendini iyileştirme teknolojisi ile geliştirilebileceğini desteklemektedir. Coope ve arkadaşlarının yaptığı bu çalışma, farklı sıcaklık koşulları altında gerçekleşen kendini iyileştirme süreçlerindeki kırılma tokluğu özelliği üzerinde durmuştur. Deneyler sonucunda kırılma tokluğu geri kazanımında oda sıcaklığında dahi yaklaşık %84 verimlilik sağlandığı, yüksek katalizör yüklemesi yapılırsa verimliliğin %352'ye kadar ulaştığı gözlemlenmiştir (Coope et al., 2014).

Yang ve arkadaşları epoksi reçine içeren mikro kapsüller kullanarak kendini iyileştiren bir antikorozyon kaplama geliştirmişlerdir. Kaplamalar çizildikten sonraki süreçte kontrol numunelerinde korozyon oluşurken çelik yüzey üzerine kaplanan epoksi mikro kapsüllü malzemede korozyon gözlenmemiş olması, polimer tabanlı bu mekanizmanın etkili iyileşmesini deneysel olarak doğrulamaktadır (Zhao et al., 2011).

Literatürde sunulan çalışmalar birlikte değerlendirildiğinde kendini iyileştiren polimerlerin özellikle polimer kompozitlerin önemli iyileşme verimliliği gösterdiği anlaşılmaktadır. Bu durum gelecekte havacılıkta otonom bakım onarım için uygulanabilirliğinde artış olmasını desteklemektedir. Polimerik malzemelerden oluşan yapılarda çoklu iyileşme dögüleri üstünde çalışmalar yapılması, böylece uzun dönemli onarım ve dayanım sağlanması sektörde büyük bir ilerleme sağlayacaktır.

Çoklu iyileşme döngüsü açısından polimerlerde içsel iyileşme mekanizmaları çözüm sunmaktadır. Literatüre göre içsel sistemler kovalent (Diels-Alder (DA) reaksiyonları, tranesterifikasyon) ve kovalent olmayan (π–π etkileşimleri, van der Waals kuvvetleri, iyonik etkileşimler, hidrojen bağları) bağlarla çalışmaktadır (Paul et al., 2025).

Kovalent sistemlerde dış bir uyaran (ısı, pH, nem vs.) ile geri dönüşümlü bağlar yeniden kurulur. 2021 yılında yayımlanan çalışmada araştırmacılar, DA reaksiyonları içeren çapraz bağlı polimer filmler üretmiş ve 0.5 mm derinliğinde çizikler oluşturmuşlardır. 120°C de sadece 5 dakika ısıtılan çiziklerin 10 dakika sonra tamamen iyileştiği gözlemlenmiştir. Numuneler soğutulduktan sonra yapılan çekme testlerinde iyileşme verimliliğinin %92,33 olduğu kaydedilmiştir (Pandey et al., 2024). Bu sonuçlar kovalent bağların kendini iyileştirme potansiyelini gösterse ve yüksek mekanik dayanım sağlasalar da, iyileşmenin gerçekleşmesi için yüksek enerji gerektirdikleri için kullanım koşullarına dikkat edilmesi gerekir. Kovalent olmayan bağlar kovalent bağlara göre daha düşük enerjilere sahip olduklarından normal sıcaklıklarda dahi kolayca oluşarak kendini iyileştirmeyi sağlayabilmektedir (Paul et al., 2025). Ancak mekanik dayanımları kovalent bağlara göre düşük olduğunu göz önüne alırsak, havacılıkta otonom bakım onarım potansiyeli sunsa da, birincil yapılarda kullanımları sınırlı kalmaktadır.

2.2 Seramik ve Metalik Malzemelerde İyileşme Mekanizmaları ve Uygulama Potansiyelleri

Seramik kompozitler kırılgan doğaları gereği üretimde ve kullanımda mikro çatlak oluşumuna yatkındır. Bu nedenle havacılık sektöründe yüksek sıcaklık koşulları altında çalışan jet motorları ve gaz türbinleri gibi uygulamalarda kullanımı kritik olan bu malzemelerin kendini iyileştirme mekanizmalarının geliştirilmesi bir gerekliliktir (Erden, 2025). Seramik malzemelerde, polimerde bahsedilen mikro kapsül ve mikrovasküler yöntemin yanı sıra oksidasyon temelli kendini iyileştirme mekanizması da yer almaktadır. Osada ve çalışma

arkadaşları seramik matrisli kompozitler ile yaptıkları çalışmada malzemenin kırılganlığına bir çözüm olarak oksidasyon temelli kendini iyileştirme mekanizmasını incelemişlerdir. Çalışmada SiC parçacıkları içeren malzemenin çatlaması sonucunda oksijenle etkileşime girerek SiO_2 fazını oluşturduğu, bu sayede çatlakları doldurduğu ve malzemenin dayanımını geri kazandırdığı gözlemlenmiştir. Bu çalışmada Si_3N_4/SiC patrikül takviyeli kompozitlerin farklı gerilme seviyelerindeki kendini iyileştirme potansiyelleri üstüne yoğunlaşılmıştır. 200 MPa uygulama gerilmesi ve 500 Pa oksijen kısmi basıncı (iyleşmenin gerçekleşmesi için gerekli olan pasif oksidasyon değeri) koşullarında bile iyileşme olduğu kaydedilmiştir (Osada et al., 2014). Oksijen kısmi basıncının artmasıyla iyileşme süresinin kısaldığı ayrıca belirtilmiştir. Bu sonuç kendini iyileştiren sistem mekanizmasının türbin koşullarında da etkin olabileceğini açıkça göstermektedir.

Metalik malzemelerin atomik yapıları ve metalik bağların özellikleri nedeniyle, kendini iyileştirme süreci polimer ve seramiklere kıyasla farklıdır (Erden et al., 2023; Hager et al., 2010). Metalik malzemeler içerisinde en dikkat çekici gruplardan biri şekil hafızalı alaşımlardır. Şekil hafızalı alaşımlar ısı değişimine bağlı olarak kristal yapısını değiştiren malzemelerdir. Bu malzemeler 2 temel faz arasında çalışırlar. Bunlar östenit (yüksek sıcaklık) fazı ve martenzit (düşük sıcaklık) fazıdır. Martenzit fazında malzeme kolay şekil değiştirebilen yumuşak bir yapıdadır. Malzeme martenzit fazındayken uygulanan yük etkisiyle malzemenin kristal düzeninde kalıcı olmayan bir değişim gerçekleşir. Malzeme ısıtıldığında değişen kristal yapı eski haline yani östenit fazına döner. Östenit fazı malzemenin orijinal geometrisinin saklandığı fazdır. Bu olaya "şekil bellek etkisi" denmektedir. Bu çalışma prensibi Şekil 4'te gösterilmektedir.



Şekil 4. Şekil hafızalı alaşımların çalışma prensibi

Eğer malzeme östenit fazındayken yük uygulanırsa uygulanan yükün etkisi malzemeyi martenzit fazına döndürür. Yük kaldırılınca tekrar östenit fazına dönerek eski şeklini alır. Bu olaya ise "süperelastisite" denir (Naresh et al., 2016).

Ti-Bi alaşımlarından oluşan tellerin kompozit içine yerleştirildiği çalışmada, tellerin şekil bellek etkisi göstermesi doğrultusunda şekil değişimlerine dayanabilmesi ve çatlak yüzeyleri arasında bağlantı oluşturması gösterilmiştir. Bu bağlantının, östenit fazı sıcaklığının üstünde ısıtılmasıyla çatlak ile ayrılmış yüzeyleri birbirine çekerek iyileşme sağladığı kaydedilmiştir. (Hager et al., 2010). Ferguson, Schultz ve Rohatgi yapmış oldukları çalışmalarında Ni-Ti şekil hafızalı alaşımları ZA-8 çinko alaşımı içine takviye olarak kullanarak kendini iyileştiren metal matrisli kompozit geliştirmişlerdir. Ni-Ti şekil hafızalı alaşım tellerin faz dönüşümü sırasında kırık yüzeyleri birbirine çektiği ve ısıl işlem sırasında matrisin erimesiyle yeniden bağ oluşturduğu gösterilmiştir. Ayrıca kullanılan numunelerin iyileşme sonrası çekme dayanımının %30'unu geri kazandığı doğrulanmıştır (Ferguson et al., 2015). Bu çalışmalar metalik malzemelerin kendini iyileştirme mekanizmaları açısından kullanılabilirliğin mümkün olduğunu göstermektedir.

3. HAVACILIKTA OTONOM BAKIM VE ONARIM SİSTEMLERİNİN ENTEGRASYONU

Otonom bakım kavramı toplam üretken bakım sisteminde kullanılan bir terimdir ve operatörlerin kendi ekipmanlarını günlük bakımını, temizlik, kontrol, yağlama ve basit ayarlamalarını kendilerinin yapmasıdır. Kısacası otonom bakım bir sistemin veya bileşenin durumunu sürekli olarak izleyebilen ve herhangi bir hasar, çatlak veya arıza durumu yaşandığında tespit eden ve gerekirse kendi kendine ihtiyaç duyulan bakımı yapabilen bir süreç bütünüdür.

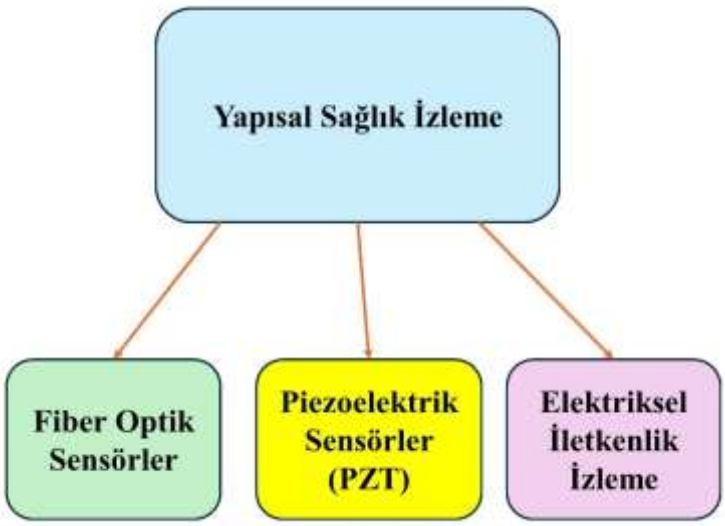
Otonom onarım ise bakımın ileri aşamalarındadır, bir sistemin veya bileşenin manuel bir müdahale bulunmadan kendi kendine onarabilmesi anlamına gelir. Otonom onarımın temeli malzeme içine yerleştirilmiş olan ve herhangi bir arıza, hasar veya olumsuz başka bir durum oluştuğunda kendi kendine reaksiyon alan onarım elemanlarına dayanır. Günümüzde otonom bakım terimi doğrudan kendini iyileştirebilen malzemelere dayanır ve otonom onarım süreçlerinin büyük bir çoğunluğu kendini iyileştirebilen malzemeler sayesinde gerçekleşir.

Kendini iyileştiren malzemeler hem servis ömrünü uzatmak hem de bakım maliyetlerini azaltmak adına önemli bir ilerlemeyi temsil eder. Genellikle hafifliğin ve yüksek mukavemetin kritik olduğu bölgelerde kullanım potansiyeli taşıyan bu malzeme türü aynı zamanda mikro hasar ve yorulma riskinin yüksek olduğu yapısal bileşenlerde ve yüzeylerde uygulama gelişimine açıktır.

Havacılıkta kullanılan birçok parça veya bileşen yüksek darbe yüküne, sıcaklığa ve yorulmalara maruz kalır. Bu sebeple mikro çatlaklar gibi küçük hasarlar bile uçuş esnasında büyük felaketlere yol açabilir. Bu felaketleri önleyebilmek adına sürekli hasar riski altında çalışan bileşenlerde otonom bakım ve onarım havacılık alanında birçok soruna çözüm olacaktır.

3.1. Yapısal İzleme ve Hasar Tespiti

Kendini iyileştirebilen malzemelerin en temel özelliği otonom onarım yetenekleridir fakat bunu gerçekleştirebilmeleri için bileşenin veya parçanın öncelikle bir hasarın var olduğunu algılayabilmesi gerekmektedir. Yapısal sağlık izleme (Structural health monitoring) havacılık yapılarının durumunu sürekli, gerçek zamanlı ve uzaktan izlemek için kullanılabilecek olan bir teknolojidir. Geleneksel bakım yöntemleri yüksek maliyet ve uzun işlem süreleri gerektirdiğinden dolayı bu yönteme alternatif olarak hasar tespitini ve onarımını tek bir döngüde birleştirerek hem vakit hem de masrafalar sınırlandırılmaya çalışılmaktadır. Yapısal sağlık izleme yapıya kalıcı olarak yerleştirilir ve zaman içinde pasif veya aktif olarak izlenebilen sensörlere dayanır. Havacılıkta üç temel sensör tipi kullanılmaktadır. Şekil 5'te havacılıkta yapısal sağlık izleme kapsamında kullanılan temel sensör tipleri gösterilmiştir. Fiber optik sensörler, piezoelektrik sensörler ve elektriksel iletkenlik izleme yöntemleri yapıların gerçek zamanlı izlenmesinde önemli role sahiptir. Bu sensörler ile yapısal bütünlük sürekli olarak kontrol edilebilmektedir.



Şekil 5. Havacılıkta yapısal sağlık izlemede kullanılan sensör tipleri

Bu sensörler, kompozit yapının izlenmesinde kullanılan fiziksel prensibe bağlı olarak statik ve dinamik rejimlerde çalışabilir. Geniş alan ölçümlerine dayalı diğer hasar ölçüm yöntemleri (ultrasonik C-taramaları, taramalı Doppler lazer hız ölçümü, termografi, vb.) YSİ geliştirmede hasarın tanımlanması ve teyidi veya önerilen YSİ yaklaşımını anlamak için kullanılabilir (Eroğlu, Diltemiz, & Kuşhan, 2022).

3.2 Kendini İyileştiren Malzemelerin Havacılık Yapılarına Entegrasyonu

Boeing 787 ve Airbus A350 gibi yeni sivil uçakların gövde kısmında %50'ye varan oranda kullanılan fiberle güçlendirilmiş polimer kompozitler darbelere karşı hassastır ve tespit edilmesi zor olan hasarlar nedeniyle bakım ihtiyacı çok fazladır. Şekil 6'da uçak gövde panellerinden kanat yapılarına kadar kompozit malzemenin kullanıldığı alanlar özetlenmekte ve böylece bakım ihtiyacının önemi göz önüne serilmektedir.



Şekil 6. Uçaklarda fiberle güçlendirilmiş polimer kompozitlerin kullanıldığı alanlar

Hem bakım ihtiyacını aşmak hem de hafif kompozit gövde tasarlamak için en umut verici çalışmalardan biri kendini iyileştiren malzemelerdir. Das, Melchior ve Karumbaiah (2011) bu

kapsamda kendini iyileştirebilen bir malzeme seçeneği hakkında çalışmalar gerçekleştirmiştir. Bu çalışmayı dikkate aldığımızda Hollow Glass Fibre malzemesi yani oyuk cam elyaflı epoksi kompozitlerinin hem darbe hassasiyetine karşı yapısal direnci arattırma potansiyeline hem de kendi kendini iyileştirebilen malzeme özelliğine sahip olduğu tespit edilmiştir. Yapılan çalışmalarda bu malzemenin hasar sonrasında eğilme dayanımında %47'ye varan bir geri kazanım gösterdiği ve karbon elyaf takviyeli epoksi laminantlarında gömülü oyuk cam elyaflı epoksiler kullanarak basma dayanımında %92'lik bir geri kazanma oranı rapor edilmiştir.

Bu duruma benzer olarak GE Aviation LEAP-1A, GE9X (Boeing 777X) ve Pratt & Whitney PW1100G-JM gibi hava araçlarının motorlarının yüksek basınçlı türbinlerinde, yanma odasında ve egzoz nozullarında seramik matrisli kompozitler (CMC) kullanılır (Paladugu et al. (2022)). Bunun sebebi oluşan yüksek ısı dereceleridir. Seramik matrisli kompozitler çok yüksek seviyede ısıya dayanabilme kabiliyetine sahiptirler. Fakat bu malzeme tipinin temel problemlerinden biri gevrek arızaya ve darbe hassasiyetlerine karşı çok hassas olmasıdır. Bu da yine yüksek bakım ihtiyacına sebebiyet vermektedir.

Paladugu et al. (2022) bu anlamda kendini iyileştirebilen seramik matrisli kompozitleri incelemiştir. Bu malzeme tipinin kendini iyileştirebilme mekanizması (örneğin Si-B-C matris + SiC lifleri) bor içerikli bileşenlerin oksitlenerek B_2O_3 (bor oksit) oluşturması ve mikro çatlakları doldurulması sayesinde gerçekleşir. Kendini iyileştirebilen bor oksit bileşenli seramik matris kompoziti hava aracı motorlarında karşımıza çıkabilecek olan 1000 °C, 1200 °C ve 1350 °C sıcaklıklarında denenmiştir (Paladugu et al., 2022). Bor bileşikleri ve bor silikon cam bileşikleri oksitlendiğinde kendi kendini iyileştirme sağlanmış ve bu da fazların matris çatlaklarına akmasına ve bunları kapatmasına yol açmıştır. Üç noktalı eğilme testi ve çekme testinden, bu CMC'lerin mukavemetinin sıcaklıkla arttığı görülmüştür. Kendi kendini iyileştirme de tetiklenmiş ve kendini iyileştiren CMC'lerin uçak motoru yanma odaları için uygun potansiyelde olduğu tespit edilmiştir.

Havacılıkta bor kullanımı daha ayrıntılı olarak incelenmiş ve bor katkılı matrise pirokarbon ilavesinin korozyon direncini ve kendi kendini iyileştirme özelliklerini artırdığı bulunmuştur. Bor katkılı pirokarbon ve B_4C ve SiC katmanları ile SiC-SiC fiber takviyeleri içeren çok katmanlı matris incelenmiş ve faz arası katmanlarda ve matrisin kendisinde bulunan bor içeren elementlerin, oksitleyici ortamda B_4C oluşturarak kendi kendini iyileştirme yeteneği sağladığı gözlemlenmiştir. Bu tür kompozitlerin mekanik yükler ve sıcaklık direnci altında mükemmel korozyon direncine sahip olduğu ve jet motoru yanma odaları için uygun olduğu tespit edilmiştir. Bor katkılı pirokarbon katmanları ve B_4C içeren çok katmanlı matrisli SiC-SiC fiber takviyeli kompozitler, mekanik yükler ve yüksek sıcaklıklar altında mükemmel korozyon direnci sergilediği yapılan çalışmalarda gösterilmiştir (Paladugu et al., 2022).

Kendini iyileştirme teknolojisi jet motorlarının türbin kanatçıklarında kullanılan nikel süper alaşımlı kanatçıkların yerine geçme potansiyeli de göstermektedir (Das et al., 2011). Kendini iyileştiren seramik kanatların kullanılması, nikel süper alaşımlı kanatların yerine geçerek daha yüksek çalışma sıcaklıklarına izin verme potansiyeline sahiptir. Daha yüksek çalışma sıcaklıkları ise doğrudan türbin verimliliğini artıracaktır. Mevcut CMC'lere nazaran kendini iyileştirme teknolojisine sahip olan bu malzeme bu sorunun üstesinden gelerek seramik kanatçıkların güvenirliğini arttırmayı amaçlamaktadır.

Şekil hafızalı polimer kompozitler özellikle askeri ve yeni sivil uçakların yapısal uygulamalarında yaygın olarak kullanılmaktadır. Airbus A350XWB ve Boeing 787 Dreamliner gibi uçaklar yapısal uygulamalarda bu malzemeyi aktif olarak kullanmaktadır. Yapılan deneysel bir çalışmaya göz attığımızda (Das et al., 2011) bir karbon elyaf takviyeli polimer matris kompozit, şekil hafızalı bir polimerin karbon nanotüpler ve karbon elyafı ile

birleştirilmesiyle yüksek basınçlı kalıplama süreci kullanılarak üretilmiştir. Yapılan deneysel çalışmalarda kompozitin yorulma sonrasında matris çatlaklarını verimli bir şekilde iyileştirdiği görülmüştür. İyileşme sonrasında orijinal mekanik özelliklerinin %72'ye kadarını geri kazandığı tespit edilmiştir. Kendi kendini iyileştiren polimer kompozitler, mevcut bazı havacılık yapısal kompozitlerinin yerini alabilir, böylece uçağın hasar toleransını, servis ömrünü ve güvenliğini artırabilir.

Tablo 2'de farklı uçak bileşenlerinde kullanılabilecek kendini iyileştirebilen malzemelerin örnekleri ve sağlanılan iyileşme düzeyleri özetlenmiştir. Gövde, motor ve aeroyapılarda hangi tür kendini iyileştirebilen malzemelerin kullanılabileceği ve ne tür performans kazanımları elde edilebileceği gösterilmektedir.

Tablo 2. Kendini iyileştiren malzemelerin havacılığa entegrasyonuyla ilgili özet

Kullanım alanı	Örnek hava aracı	Aktif kullanılan malzeme	Kendini iyileştirebilen malzeme seçeneği	Kendini iyileştirebilme düzeyi
Gövde	Boeing 787 ve Airbus A350	Fiberle güçlendirilmiş polimer kompozit	Oyuk cam elyaflı epoxy kompoziti	%47
Motor ve yüksek sıcaklık oluşan bölgeler	GE Aviation LEAP-1A, GE9X (Boeing 777X) ve Pratt & Whitney PW1100G-JM	Seramik matrisli kompozitler	Kendini iyileştirebilen kendini iyileştirebilen seramik matrisli kompozit. (örneğin Si-B-C matris + SiC lifleri)	Hem sıcaklık hem de mukavemet direnci büyük oranda artmıştır
Aeroyapılar	Airbus A350XWB ve Boeing 787 Dreamliner	Şekil hafızalı polimer kompozitler	Karbon elyaf takviyeli polimer matris kompozit, şekil hafızalı bir polimerin karbon nanotüpler ve karbon elyafı ile birleştirilmesi	%72

4. TEKNİK ZORLUKLAR VE GELECEK PERSPEKTİFLERİ

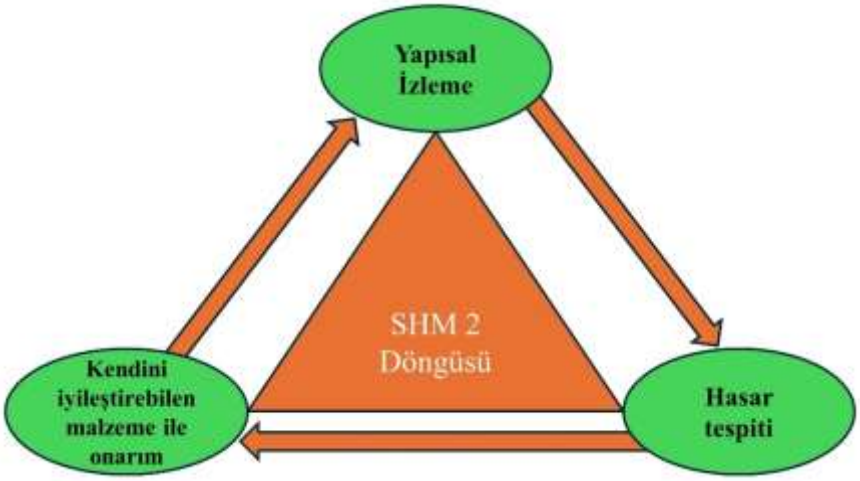
Kendini iyileştirebilen malzemelerin havacılık uygulamalarında kullanımı hem bakım maliyetlerini azaltması hem yapısal güvenliğin arttırması sebebiyle büyük potansiyel taşıyor fakat uygulanabilirlik, performans süresi gibi çeşitli teknik konularda bazı zorluklar bulunduruyor.

4.1 Teknik Zorluklar

Havacılıkta kullanılan bileşenler ve parçalar çok yüksek termal döngülere, UV radyasyonuna, kuvvetli titreşim yüklerine ve çeşitli basınç ortamlarına maruz kalmaktadır. Otonom bakım sağlayabilen kendini iyileştirebilen malzemelerin bu koşullara ayak uydurabilmesi hala önemli bir sorundur ve tam olarak netlik kazanmış durumda değildir (Erden, 2025). Özellikle mikro kapsüllerin kırılma dayanımı ve iyileştirici stabilitesi kritik sınırlayıcı faktörlerden birdir. Bir diğer teknik zorluk ise havacılık alanında kullanılan kompozitlerde kendini iyileştirme mekanizması eklemenin çoğu zaman imalat sırasında malzemenin özgül dayanımını azaltabiliyor olmasıdır. Mikro kapsül veya damar ağlarının kompozit içinde oluşturduğu boşluklar uzun dönem yorulma durumunu tetikleyebilmektedir. Özellikle vasküler ağların entegre edilmesi yapıya ilave boşluklar ve dolayısıyla ek ağırlık ya da hacim getirir (Tsilimigkra et al., 2016). Mikro kapsül tabanlı sistemlerin imalat sırasında özgül dayanımının azalması dışında bu sistemlerin çoğu tek seferlik iyileştirme sağlamaktadır ve uçağın ömrü boyunca tekrar eden mikro çatlakların onarımı için çok döngülü sistemler henüz yeterince geliştirilmemiştir (Cordier et al., 2008).

4.2 Gelecek Perspektifleri

Bu konuda özellikle bahsedilmesi gereken yöntem SHM2 yöntemidir. Bu yöntem yapısal sağlık izleme yöntemiyle kendini iyileştirebilen malzemelerin bir döngü halinde onarım yapabilmesini amaçlamaktadır (Haider, Srivastava, Rohatgi & Salowitz, 2024). Bu çalışma sayesinde hem hasar tespiti hem de onarım tetiklenecek ve hava araçlarında bakım ve onarım süreçleri otomatikleşecektir. Yapısal sağlık izleme ile kendini iyileştiren malzemelerin entegre edildiği SHM2 yöntemi ve bu yöntemin bir kapalı döngü halinde nasıl işlediği Şekil 7'de gösterilmektedir. Bu döngü hasarın sensörler tarafından tespit edilmesi ile başlar ve daha sonrasında kendini iyileştiren malzemeler devreye girerek onarım gerçekleştirmesiyle devam eder.



Şekil 7. SHM2 Döngüsü

Otonom bakım ve onarım yeteneğine sahip sistemlerin geliştirilmesi, havacılık endüstrisinde yapısal güvenirlik ve süreklilik açısından önemli bir araştırma konusu ve geleceğe yönelik önemli bir atılım haline gelmiştir. Eroğlu et al. (2022) çalışmasında bahsettiği yapısal sağlık izleme tekniği sayesinde bir parça veya bileşene yerleştirilen sensörler aracılığıyla hasarın konumu ve boyutu tespit edilebilmekte olduğunu ancak tespit edilen hasarın yine insan müdahalesiyle onarılması gerektiğini belirtmiştir. Bu durum hem zaman hem de maliyet artışına sebebiyet vermektedir. Haider et al. (2024) yapısal sağlık izleme ve kendini iyileştirebilen malzemelerin entegrasyonu sonucunda SHM2 döngüsünden bahsetmektedir. Bu döngü sayesinde hava aracında hasar gören bileşenlerde hem hasar tespitini hem de onarım sürecini otomatik olarak tetikleyen kapalı bir döngü mümkün kılınabilmektedir.

Çalışmada nikel-titanyum (NiTi) şekil hafızalı alaşım (SMA) lifleriyle güçlendirilmiş bizmut-kalay (BiSn) matrisi kullanılmıştır. Kullanılan malzeme hem yük taşıma kapasitesine sahip olması hem de hasar sonrası ilk mukavemet seviyelerine yakın değerlere ulaşabilmesiyle dikkat çekmiştir. Yapısal sağlık izleme için kullanılan piezoelektrik sensörler hasar seviyesini ultrasonik sinyal değişimlerine göre ölçmüş, ardından malzeme ısıtılarak NiTi teller aktive edilmiş ve kompozit yapı kendi kendini başarıyla iyileştirmiştir. Ancak, yapılan işlemler sırasında piezoelektrik sensörlerden biri ayrılmakta olup hem piezoelektrik sensörünün yeniden yapıştırma gerekliliği hem de sistemlerin entegrasyonu sırasasında yaşanan zorluklar başarılı bir sistem entegrasyonu için daha fazla araştırma gerektiğini göstermiştir. Bu çalışmaya gelecek perspektifi gözüyle bakılırsa ilk sonuçlar, otonom hasar tespiti ve kendi kendini iyileştiren malzemelerin kombinasyonu olan SHM2 sistemlerinin otonom bakım ve onarım için umut verici olduğunu göstermektedir.

5. SONUÇ

Kendini iyileştiren malzemelerin havacılıkta otonom bakım onarım uygulamalarına uyarlanması, literatürde belirtilen bulguların ışığında hem önemli bir potansiyel hem de belirgin sınırlamalar barındırmaktadır. İncelenen çalışmalar ile yapılan değerlendirmelerde, ısı girdisinin kontrol gereksiniminin veya iyileşme verimi ile mekanik dayanım arasında kurulmak istenen dengenin en belirgin sınırlamalardan olduğu görülmüştür. Bu bağlamda özellikle havacılıkta çok yaygın kullanılan kompozit yapıların iyileşme sonrası kapasitesinin korunması, tekrarlı iyileşmenin gelişimi ve bu mekanizmaların hava araçlarının asıl servis koşullarındaki davranışları üzerinde durulması gerektiği sonucuna varılmıştır. Kendini iyileştirme mekanizmalarının uzun dönemli davranışlarının hem içsel hem dışsal olmak üzere oluşturulacak hibrit sistem çalışmalarının ve yapısal izleme yöntemi ile döngü halinde işleyen mekanizmaların incelenmesinin önemli olduğu düşünülmektedir.

Genel olarak değerlendirildiğinde havacılık sektöründeki yüksek güvenlik standartlarının da bu malzemelerin kullanımının henüz yaygınlaşmamış olmasının sebeplerinden birisi olarak görülebilir. Dolayısıyla teknolojinin ve araştırmaların ilerlemesi ile kendini iyileştirme mekanizmalarında mekanik kaybın minimize edilmesi, uzun ömürlü, hızlı ve tekrarlı iyileşmenin geliştirilmesi beklenmektedir. Sonuç olarak maliyetleri düşürecek ve sürdürülebilirliği artıracak olan bu malzemelerin geleceğin otonom bakım onarım sistemlerinde kritik rol üstleneceği öngörülmektedir.

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KONTROLLÜ M-CRESOL GERİ KATKILAMASI İLE A-SWNT/POLİ(ANİLİN-KO-AKRİLONİTRİL) KOMPOZİTLERİNİN TERMOELEKTRİK ÖZELLİKLERİNİN OPTİMİZASYONU

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ÖZET

Günümüzde artan enerji ihtiyacı ve küresel ölçekte yaşanan enerji krizi, sürdürülebilir ve yüksek verimli enerji dönüşüm teknolojilerinin geliştirilmesini zorunlu hâle getirmektedir. Bu bağlamda, atık ısının doğrudan elektrik enerjisine dönüştürülmesine olanak sağlayan termoelektrik malzemelere yönelik ilgi son yıllarda belirgin biçimde artmıştır. Termoelektrik malzemeler arasında, karbon nanotüpler (CNT) ile iletken polimerlerin oluşturduğu kompozitler özel bir önem taşımaktadır; çünkü bu yapılar mekanik esneklik ile görece yüksek termoelektrik verimi harmanlayabilmektedir. Bu çalışmada, geri katkılama (re-doping) işlemi sırasında kullanılan m-cresol miktarının, amin fonksiyonlu tek duvarlı karbon nanotüp/poli(anilin-ko-akrilonitril) kompozitlerinin termoelektrik özellikleri üzerindeki etkisi incelenmiştir. Kompozitler, aynı polimerizasyon koşulları altında sentezlenmiş ve ardından farklı m-cresol oranlarında (%0,60– %0,72 – %0,90 – %1,20,- %1,80,- %3,60 w/w) geri katkılanmıştır. Geri katkılama işlemi oda sıcaklığında yapılmış ve sonrasında yapılan ölçümlerle elektriksel iletkenlik (σ), Seebeck katsayısı (S) ve güç faktörü (PF = $S^2\sigma$) değerleri belirlenmiştir. Sonuçlar, m-cresol oranındaki artışın belirli bir düzeye kadar (yaklaşık %1,20) zincir hizalanmasını ve taşıyıcı hareketliliğini önemli ölçüde artırdığını göstermiştir. Bu oranda, polimer zincirleri arasındaki π–π etkileşimleri güçlenmiş ve optimum iletkenlik–Seebeck katsayısı dengesi elde edilmiştir. En yüksek güç faktörü yaklaşık 149,1 μW/mK^2 olarak %1,20 m-cresol içeriğinde kaydedilmiştir. %1,20'nin üzerindeki oranlarda ise aşırı çözücü etkileşimi nedeniyle morfolojik bozulmalar ve termolektrik verimde düşüş gözlenmiştir. Elde edilen bulgular, geri katkılama sırasında m-cresol miktarının dikkatle kontrol edilmesinin, polimer-nanotüp arayüzünde yük taşınımını optimize ederek termoelektrik performansı artırmada kritik rol oynadığını ortaya koymaktadır.

Anahtar kelimeler: anilin, akrilonitril, kopolimer, termoelektrik, m-kresol

OPTIMIZATION OF THERMOELECTRIC PROPERTIES IN A-SWNT/ POLY(ANILINE-CO-ACRYLONITRILE) COMPOSITES VIA CONTROLLED M-CRESOL RE-DOPING

ABSTRACT

The increasing global demand for energy and the ongoing energy crisis necessitate the development of sustainable and high-efficiency energy conversion technologies. In this context, thermoelectric materials have gained significant attention in recent years, owing to their ability to convert waste heat. Among various thermoelectric materials, composites of carbon nanotubes (CNTs) and intrinsically conducting polymers receive a particular interest, as they combine mechanical flexibility with reasonable power output. However, the thermoelectric efficiency of CNT/polymer composites highly depends on processing conditions, especially the choice and amount of secondary dopants used to modify chain ordering. In this study, we investigated the effect of m-cresol amount on the thermoelectric performance of amine-functionalized single-walled carbon nanotube/poly(aniline-co-acrylonitrile) composites. The composites were synthesized under identical polymerization conditions, and subsequently re-doped with different m-cresol contents (0.60%, 0.72%, 0.90%, 1.20%, 1.80%, 3.60% w/w). The re-doping procedure was carried out at room temperature, and then, the electrical conductivity (σ), Seebeck coefficient (S), and power factor (PF = $S^2\sigma$) values were determined. The results showed that increasing the m-cresol content enhanced chain alignment and charge carrier mobility up to a certain level (approximately 1.20%). At this ratio, π–π interactions between polymer chains were strengthened, leading to an optimal balance between conductivity and Seebeck coefficient. The highest power factor, approximately 149.1 $\mu W/mK^2$, was recorded at 1.20% m-cresol content. At ratios above 1.20%, morphological degradation and a decline in thermoelectric performance were observed due to excessive solvent–polymer interactions. The findings demonstrate that careful control of the m-cresol amount during re-doping plays a critical role in enhancing thermoelectric performance by optimizing charge transport at the polymer–nanotube interface.

Keywords: aniline, acrylonitrile, copolymer, thermoelectric, m-cresol

1. GİRİŞ

Yenilenebilir enerji kaynakları, sürdürülebilir enerji üretiminde kritik bir konuma sahip olsa da, mevcut teknolojilerin verimliliğinin artırılması için atık ısının değerlendirilmesine yönelik çözümlere ihtiyaç duyulmaktadır. Bu kapsamda, güneş enerjisi sistemleri gibi yenilenebilir teknolojilerde açığa çıkan kullanılmamış ısının geri kazanılması, enerji dönüşüm zincirinin önemli bir halkasını oluşturur (Katirci et al., 2023). Küresel ölçekte artan enerji talebi ve fosil yakıt kullanımının çevresel etkileri, sürdürülebilir enerji teknolojilerinin geliştirilmesini kritik hâle getirmektedir. Yenilenebilir enerji sistemlerinde ortaya çıkan atık ısının büyük oranda değerlendirilemeden kaybedilmesi, enerji dönüşüm süreçlerinde önemli bir verimlilik kaybı oluşturmaktadır (Erden et al., 2025).

Termoelektrik (TE) malzemeler, atık ısıyı doğrudan elektrik enerjisine dönüştürebilme kabiliyetleri sayesinde enerji verimliliğini artırma ve karbon emisyonlarını azaltma açısından önemli bir çözüm sunmaktadır (He & Tritt, 2017). Özellikle düşük sıcaklık farklarının hakim olduğu sistemlerde organik ve hibrit TE malzemeler, esneklikleri, düşük maliyetleri ve çevresel uyumlulukları nedeniyle giderek daha fazla ilgi görmektedir (Zhang & Zhu, 2017; Du et al., 2018).

Geleneksel inorganik termoelektrik malzemeler olan Bi_2Te_3, PbTe ve $CoSb_3$ gibi bileşikler yüksek performans göstermelerine rağmen, toksisite, işlenebilirlik zorlukları ve kırılganlık gibi dezavantajlara sahiptir (Yan et al., 2011; Zebarjadi et al., 2012). Buna karşın iletken polimerler ve karbon nanotüp (CNT) tabanlı kompozitler, düşük ısıl iletkenlikleri ve çözeltide işlenebilir olmaları sayesinde yeni nesil esnek termoelektrik uygulamalar için güçlü adaylar olarak değerlendirilmektedir (Du et al., 2018; Chen et al., 2012).

İletken polimerler arasında polianilin (PANI), protonlanabilir yapısı, çevresel kararlılığı ve doping seviyesine bağlı olarak ayarlanabilir elektriksel özellikleri nedeniyle organik termoelektrik çalışmalarda öne çıkan malzemelerden biridir (Ozbay et al., 2023; MacDiarmid, 1997). PANI'nin akrilonitril (AN) ile kopolimerizasyonu, mekanik dayanımın artırılması önemli bir katkı olarak ön plana çıkmaktadır (Virji et al., 2006). Buna ek olarak, tek duvarlı karbon nanotüplerin (SWNT) polimer matrisine eklenmesi, yüksek taşıyıcı hareketliliği ve çoklu iletken ağ yapısı sayesinde Seebeck katsayısını ve güç faktörünü iyileştirmektedir (Chen et al., 2012; Lee et al., 2016).

Organik kompozitlerde nihai termoelektrik performansı belirleyen en kritik adımlardan biri ise **ikincil katkılama (re-doping)** sürecidir. Özellikle geri katkılamanın m-cresol gibi çözücü ortamların da gerçekleştirilmesi, PANI zincirlerinin daha planarlı bir konformasyona geçmesini sağlayarak zincir hizalanmasını, π–π istiflenmesini ve taşıyıcı hareketliliğini artırmaktadır (MacDiarmid, 1997; Gospodinova & Terlemezyan, 1998). Literatür, m-cresol ile yapılan bu yapı geçişinin hem elektriksel iletkenlik hem de Seebeck katsayısı/iletkenlik dengesi üzerinde belirgin iyileşme sağladığını göstermektedir (MacDiarmid, 1997; Zhang & Zhu, 2017).

Bu bağlamda, m-cresol miktarının hassas biçimde kontrol edilmesi, polimer–nanotüp arayüzündeki yük taşınım yollarını optimize etmek, taşıyıcı hareketliliğini artırmak ve kompozitin termoelektrik performansını maksimize etmek açısından kritik bir araştırma parametresi olarak değerlendirilmektedir. Bu çalışma, A-SWNT/Poli(ANI-ko-AN) kompozitlerinde farklı m-cresol oranlarına bağlı olarak meydana gelen yapısal ve elektriksel değişimleri sistematik biçimde inceleyerek optimum re-doping seviyesini belirlemeyi amaçlamaktadır.

2. MATERYAL VE YÖNTEM

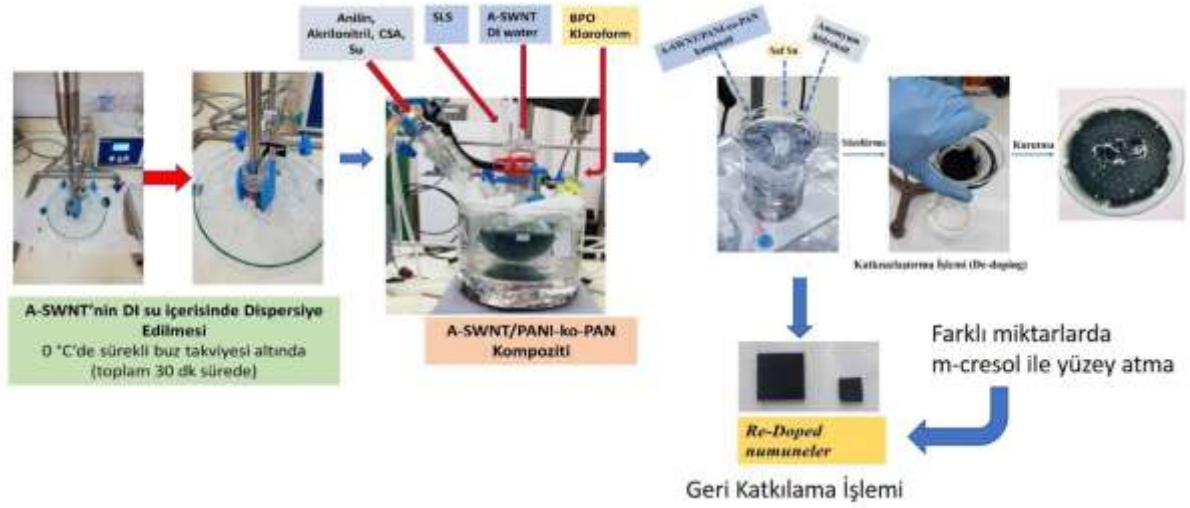
Bu çalışmada kullanılan amin fonksiyonlu karbon nanotüpler (A-SWNT) Cheaptubes firmasından tedarik edilmiştir. Kloroform ($CHCl_3$) ve Soda-Lime Glass (SLG) cam altlıklar ISOLAB Chemicals, sodyum lauril sülfat (SLS) ise Fisher Chemical'dan sağlanmıştır. Kamfor sülfonik asit (CSA), benzoil peroksit (BPO), akrilonitril, anilin, m-cresol ve amonyum hidroksit Sigma-Aldrich ürünleri olup, deneylerde yalnızca anilin ön saflaştırma amacıyla damıtılmış; diğer tüm kimyasallar satın alındığı şekliyle kullanılmıştır. Tüm deneysel süreçlerde saf su tercih edilmiştir.

İlk aşamada A-SWNT'ler, su içerisinde homojen bir dağılım elde etmek amacıyla Bandelin HD2070 ultrasonik homojenizatör kullanılarak disperse edilmiştir. Başlatıcı olarak kullanılan BPO, kloroform içinde çözündürüldükten sonra polimerizasyonun yürütüleceği üç boyunlu balona aktarılmış ve çözücü kaybını önlemek için sisteme geri soğutucu bağlanmıştır. Saflaştırılmış anilin su içerisinde çözündürüldükten sonra akrilonitril ve katkılayıcı CSA belirli bir süre karıştırılarak çözeltiye eklenmiştir. Bu monomer karışımı daha sonra kontrollü olarak reaktöre damlatılmıştır. Reaksiyon karışımına, polimerizasyon ortamında kararlı bir emülsiyon yapısı oluşturmak amacıyla SLS eklenmiş; A-SWNT'lerin disperse edildiği süspansiyon ise uygun karıştırma süresi sonunda reaktöre ilave edilmiştir.

Polimerizasyonun sabit sıcaklıkta ilerlemesini sağlamak için su banyosu kullanılmış ve banyo sıcaklığı 60 °C'de tutulmuştur. Bu koşullarda polimerizasyon ortamının yaklaşık 55 °C'de seyrettiği belirlenmiş ve BPO'nun bu sıcaklıkta termal olarak bozunarak reaksiyonu başlattığı değerlendirilmiştir. Tüm polimerizasyon süreci 24 saat boyunca bu sıcaklıkta sürdürülmüştür. Reaksiyonun tamamlanmasının ardından kompozitler yaklaşık 25 °C'de aseton ile çöktürülmüş, elde edilen katı ürün süzülerek ayrılmış ve 45 °C'de vakumda kurutulmuştur. Numuneler daha sonra üç kez aseton ve üç kez saf su ile yıkanarak safsızlıklardan arındırılmış ve sabit kütleye ulaşana kadar yeniden kurutulmuştur.

Kurutulan kompozitlere katkı giderme işlemi uygulanmış; bu amaçla örnekler 0,1 M amonyum hidroksit çözeltisi içerisinde oda sıcaklığında yaklaşık 12 saat karıştırılmıştır. Bu işlemin ardından tekrardan vakum altında kurutulan numuneler farklı oranlarda m-cresol (%0,60 – %0,72 – %0,90 – %1,20 – %1,80 – %3,60 w/w) ile kopolimer/CSA molar oranı 2:1 olacak şekilde 24 saat karıştırılarak yeniden katkılanmıştır. Bu işlem sırasında m-cresol'ün polimer zincirlerini genişletmesi ve π–π etkileşimlerini artırması hedeflenmiştir. Yeniden katkılama aşamasından sonra kompozitler damla döküm yöntemiyle SLG cam altlıklar üzerine kaplanmış ve ince film hâline getirilmiştir. Tüm üretim süreci Şekil 1'de şematik olarak gösterilmiştir.

Üretilen ince filmlerin termoelektrik performansını belirlemek amacıyla çeşitli karakterizasyon yöntemleri uygulanmıştır. Kimyasal yapı Bruker Tensor II FT-IR spektrometresi ile incelenmiş, film kalınlıkları Taylor Hobson A profilometresiyle ölçülmüştür. Elektriksel iletkenlik değerleri ECOPIA HMS-7000 cihazı kullanılarak dört nokta prob yöntemi ile oda sıcaklığında belirlenmiştir. Kompozitlerin yüzey morfolojisi TESCAN MIRA 3 XMU taramalı elektron mikroskobunda görüntülenmiş, termoelektrik özellikler ise Linseis LSR-3/800 sistemi ile Seebeck katsayısı ve elektriksel direnç ölçümleri yapılarak değerlendirilmiştir.



Şekil 1. A-SWNT/Poli(ANI-ko-AN) kompozitlerinin sentezi ve geri katkılanması

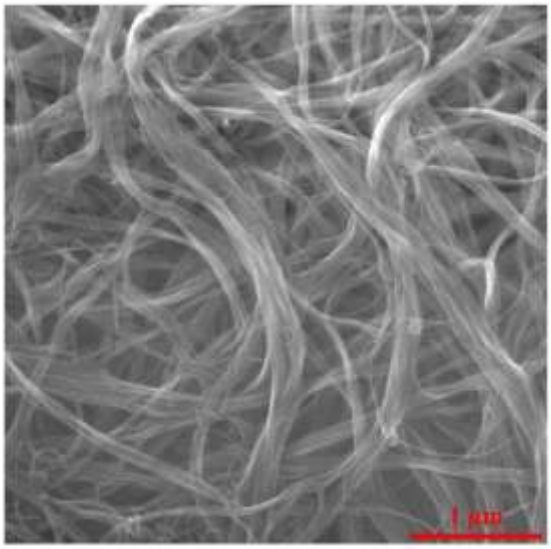
3. BULGULAR VE TARTIŞMA

Bu araştırmada, A-SWNT/Poli(ANI-ko-AN) kompoziti üretilmiş ve farklı miktarlarda m-cresol ile geri katkılamanın termoelektrik özelliklerine olan etkileri incelenmiştir. Sonuçlar, m-cresol oranı arttıkça polimer zincirlerinin hizalanmasının güçlendiğini ve taşıyıcı hareketliliğinin belirli bir noktaya kadar önemli ölçüde arttığını göstermiştir. Tablo 1'de görüldüğü üzere yaklaşık **%1,20 m-cresol** seviyesine kadar elektriksel iletkenlikte belirgin bir artış gözlenmiş, bu seviyede polimer-zincir düzeni maksimuma ulaşmıştır.

Tablo 1. m-cresol çözücüsü kullanılarak hazırlanan PANI/CSA sistemine ait çözelti parametreleri.

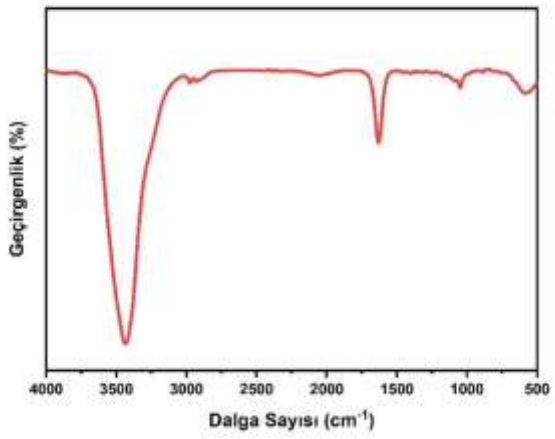
Solvent (mL)	PANI (mg)	CSA (mg)	Katı Kütle (mg)	Katı Kütle / Solvent % (w/w)
1	16	19,95	35,95	3,60
2	16	19,95	35,95	1,80
3	16	19,95	35,95	1,20
4	16	19,95	35,95	0,90
5	16	19,95	35,95	0,72
6	16	19,95	35,95	0,60

Şekil 2'tde farklı m-cresol oranları kullanılarak geri katkılanmış A-SWNT/Poli(ANI-ko-AN) kompozitlerine ait taramalı elektron mikroskobu (SEM) görüntüleri sunulmaktadır. Görsellerden, m-cresol miktarındaki değişimin A-SWNT morfolojisi üzerinde belirgin bir yapısal dönüşüme yol açmadığı anlaşılmaktadır. Tüm geri katkılama seviyelerinde nanotüplerin polimer matris içerisinde benzer konformasyon sergilediği ve kompozit yapıda A-SWNT'lerin homojen bir şekilde dağıldığı gözlemlenmiştir. Bu durum, re-doping sürecinin nanotüp ağ yapısını bozmadığını ve polimer–nanotüp arayüzünde sürekliliğin korunduğunu göstermektedir.



Şekil 2. Hazırlanan A-SWNT kompozitler için SEM görüntüleri.

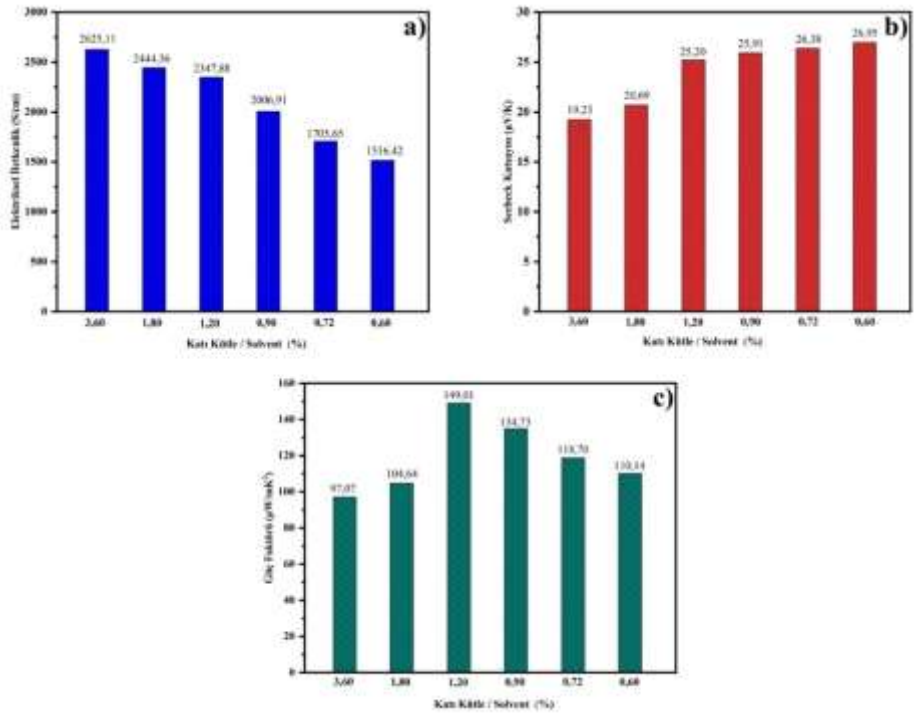
Şekil 3'te A-SWNT içeren kompozitlere ait FTIR spektrumları sunulmakta olup, elde edilen sonuçların literatürde raporlanan bulgularla uyumlu olduğu görülmektedir (Erden et al., 2024). Spektrumlarda yaklaşık 3400 cm^{-1} bölgesinde gözlenen geniş bandın, su moleküllerine ait O–H gerilme titreşimlerinden kaynaklanabileceği değerlendirilmektedir. Bu bandın şiddetindeki değişimin, FTIR analizinde kullanılan KBr pelletlerinin nem içeriğine veya ölçüm sırasında ortamda bulunan rutubet seviyesine bağlı olarak farklılık gösterebileceği düşünülmektedir. FTIR spektrumlarında gözlemlenen 1630 cm^{-1} civarındaki karakteristik pik ise C=C iskelet gerilme titreşimlerine atfedilmekte olup, bu pik tüm kompozit numunelerinde belirgin biçimde ortaya çıkmıştır (Erden et al., 2025). Söz konusu bant, A-SWNT/kopolimer kompozit yapısının başarıyla oluştuğunu doğrulayan temel titreşim modlarından biri olarak kabul edilmektedir (Fernandes et al., 2019). Beklendiği üzere, saf A-SWNT'nin FTIR spektrumu 1630 cm^{-1} bölgesindeki söz konusu pik dışında genel olarak düşük şiddet yoğunluklarına sahiptir. Kompozit numunelerin FTIR davranışı incelendiğinde, spektral özelliklerin büyük ölçüde kopolimer matrisinin karakteristik titreşim modlarını yansıttığı görülmektedir.



Şekil 3. Hazırlanan a-SWNT kompozitlerinin de-doping sonrası FT-IR spektrumu.

A-SWNT/Poli(ANI-ko-AN) kompozitlerinin farklı m-cresol oranlarında geri katkılanmasına ilişkin elde edilen elektriksel ve termoelektrik veriler, m-cresol miktarının malzemenin taşıyıcı

taşınım mekanizması üzerinde belirleyici bir etkiye sahip olduğunu ortaya koymaktadır. Şekil 4a'da görüldüğü üzere, yüksek m-cresol oranlarında (örneğin %3,60 ve %1,80) kompozitlerin elektriksel iletkenliği belirgin şekilde artmış ve bu durum m-cresolün PANI zincirlerinin konformasyonunu "expanded-coil" formuna dönüştürerek π–π istiflenmesini güçlendirmesiyle açıklanabilir (MacDiarmid, 1997; Gospodinova & Terlemezyan, 1998). Ancak m-cresol oranı azaltıldığında zincirler arası planarlık ve taşıyıcı hareketliliği azalmakta, bu da iletkenliğin düşmesine yol açmaktadır. Bu bulgu, polimer matrisinde doping seviyesinin artmasıyla taşıyıcı yoğunluğunun yükseldiğini ve sonuç olarak iletkenliğin arttığını bildiren literatür ile uyumludur (Zebarjadi et al., 2012). Buna karşılık, Seebeck katsayısı Şekil 4b'de görüldüğü üzere iletkenliğin aksine düşük m-cresol oranlarında artış göstermiştir. En yüksek S değeri %0,60 m-cresol içeriğinde elde edilmiş olup, m-cresol miktarının yükselmesiyle Seebeck katsayısı düşmektedir. Bu durum termoelektrik malzemelerde iyi bilinen σ–S trade-off davranışıyla ilişkilidir; taşıyıcı yoğunluğunun artması iletkenliği artırırken Seebeck katsayısını düşürmektedir (He & Tritt, 2017). Dolayısıyla yalnızca iletkenliğin yüksek olması, optimum termoelektrik performansın elde edildiği anlamına gelmemektedir; Seebeck katsayısının korunması için kontrollü bir doping seviyesine ihtiyaç duyulmaktadır. Güç faktörü ($PF = S^2\sigma$) değerlerinin yer aldığı Şekil 4c ise bu iki parametre arasındaki rekabetin optimum noktada birleştiği doping seviyesini açıkça göstermektedir. PF değerinin %1,20 m-cresol içeriğinde maksimuma ulaşması, bu oranında hem yeterli zincir hizalanması sağlayacak bir iletkenlik artışı yarattığını hem de Seebeck katsayısındaki düşüşün henüz kritik seviyeye ulaşmadığını göstermektedir. Benzer şekilde, organik termoelektrik kompozitlerde optimum performansın genellikle orta seviyelerdeki doping oranlarında ortaya çıktığı literatürde de vurgulanmaktadır (Zhang & Zhu, 2017; Chen et al., 2012). Bu nedenle, bu çalışmada belirlenen %1,20 m-cresol oranı, taşıyıcı hareketliliği ile enerji filtreleme etkisi arasında en uygun dengenin sağlandığı, dolayısıyla termoelektrik performansı maksimize eden optimum geri katkılama seviyesini temsil etmektedir.



Şekil 4. A-SWNT/Poli(ANI-ko-AN) kompozitlerinin TE özellikleri a) Elektriksel iletkenlik, b) Seebeck, c) Güç faktörü

4.SONUÇ

Bu çalışmada, A-SWNT/Poli(ANI-ko-AN) kompozitlerinde farklı m-cresol seviyelerinde gerçekleştirilen geri katkılama işleminin termoelektrik performans üzerindeki etkileri kapsamlı biçimde değerlendirilmiştir. Bulgular, m-cresol miktarının polimer zincir hizalanmasını ve taşıyıcı hareketliliğini doğrudan etkilediğini, bu nedenle termoelektrik parametrelerde belirgin değişimler oluşturduğunu göstermiştir. Elektriksel iletkenlik ve Seebeck katsayısı arasındaki denge göz önüne alındığında, optimum performansın %1,20 m-cresol içeriğinde elde edildiği belirlenmiş ve bu seviyede en yüksek güç faktörü kaydedilmiştir. Sonuç olarak, m-cresol oranının kontrollü ayarlanması, polimer–nanotüp arayüzünde yük taşınımını optimize ederek esnek organik termoelektrik kompozitlerin verimini artırmada kritik bir parametre olarak ortaya çıkmaktadır.

TEŞEKKÜR

Bu çalışma “Termoelektrik Malzeme Olarak Karbon Nanotüp/Kopolimer Kompozitlerinin Geliştirilmesi” başlıklı ve 221M082 numaralı Tubitak-1001 projesi tarafından desteklenmiştir.

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5G 1x2 MIMO YAMA ANTENLERDE DGS KULLANILARAK İZOLASYONUN İYİLEŞTİRİLMESİ

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ÖZET

Günümüzde kablosuz iletişim teknolojilerinde yaşanan hızlı gelişmeler, yeni gereksinimleri ortaya çıkarmıştır. Bu taleplere karşılık geliştirilen beşinci nesil (5G) mobil iletişim teknolojisi, yalnızca geleneksel haberleşme yöntemlerini dönüştürmekle kalmamış, aynı zamanda anten sistemlerinin de yeniden tasarlanmasını zorunlu hale getirmiştir. Avrupa Komisyonu tarafından 3.5 GHz bandının kullanımı özellikle 5G uygulamaları için çok kritik bir konumdadır. MIMO mikroşerit antenler, 5G gereksinimlerini karşılamak için ideal bir teknolojidir. MIMO sistem tasarımlarında en önemli zorluk, anten elemanlarının yakın yerleşiminden doğan karşılıklı kuplajın azaltılması ve sistem performansının artırılmasıdır. Bu çalışmada, nihai olarak tasarlanan 1x2 MIMO anten yapısı 3.5GHz çalışma frekansında faaliyet gösterecek şekilde optimize edilmiştir. Anten yapısının ön yüzeyinde birbirine özdeş yama antenler olup, aralarındaki elektromanyetik etkileşimi azaltmak amacıyla dambıl şekline benzer bir izolasyon yapısı tasarlanmıştır. Anten tasarımının DGS yapısı için toprak düzleminde, simetrik olarak tasarlanan iki yarım dairesel şeklin dışında kalan alan ile ortada konumlanan bir dikdörtgen boşluk yer almaktadır. Bu yapı, yüzey akımlarının yönünü değiştirerek akımların doğrudan diğer anten elemanına bağlanmasını engeller. Böylece karşılıklı bağlaşım azaltılırken, antenin MIMO performansı iyileştirilmiş olur. Simülasyon çalışmalarında en iyi anten performansını gözlemlemek için iki farklı izolasyon ve DGS tasarımı ayrı ayrı incelenerek grafikler üzerinden karşılaştırılmalı analizi yapılmıştır. Sonuç olarak yalın anten modeline göre seçilen izolasyonlu DGS eklenmiş anten tasarımının 3.5GHz çalışma frekansında hem geri dönüş kaybında 11dB'e hem de izolasyon kaybında 6dB'e yakın bir iyileştirme sağladığı ayrıca tasarımın 2.9dBi mertebelerinde bir kazanç elde ettiği gözlemlenmiştir. Literatürdeki diğer çalışmalara kıyasla 80x50mm boyutlarına indirgenmiş olması, 5G teknolojisinin gerektirdiği yüksek performanslı, küçük boyutlu ve enerji tasarruflu anten çözümleri için önemli bir avantaj sunmaktadır. Elde edilen bulgular, gelecekte daha gelişmiş kablosuz haberleşme uygulamalarında kullanılabilecek kompakt ve yüksek verimli antenlerin geliştirilmesine katkı sağlayacaktır.

Anahtar Kelimeler: 5G, Patch Anten, MIMO, 3.5GHz, İzolasyon, DGS

ENHANCEMENT OF ISOLATION IN 5G 1×2 MIMO PATCH ANTENNAS BY EMPLOYING DEFECTED GROUND STRUCTURE (DGS)

ABSTRACT

Recent advances in wireless communication technologies have introduced new demands. The fifth-generation (5G) mobile communication system, addressing these needs, has transformed conventional methods and required the redesign of antenna systems. The 3.5 GHz band, designated by the European Commission, is critical for 5G applications. MIMO microstrip antennas represent an ideal technology to meet the requirements of 5G systems. The major challenge in MIMO system design is to minimize the mutual coupling arising from the close placement of antenna elements and enhance overall system performance. In this study, the proposed 1×2 MIMO antenna structure was optimized to operate at the 3.5 GHz frequency band. On the front surface of the antenna, identical patch elements are placed, and a dumbbell-shaped isolation structure was designed to reduce the electromagnetic interaction between them. On the ground plane of the antenna, the DGS structure comprises vacant regions surrounding the two symmetrically designed semi-circular shapes and a centrally positioned rectangular slot. This configuration alters the direction of the surface currents, preventing them from directly coupling to the other antenna element. Consequently, mutual coupling is reduced, and the MIMO performance of the antenna is improved. In the simulation studies, two different isolation and DGS designs were individually examined to observe the optimal antenna performance, and a comparative analysis was conducted based on the obtained graphs. As a result, compared to the basic antenna model, the DGS structure achieved an improvement of approximately 11 dB in return loss and 6 dB in isolation loss at the 3.5 GHz. Furthermore, the design exhibited a gain of around 2.9 dBi. Also, the 80x50 mm dimensions compared to other studies offer a significant advantage for required high-performance, compact, and energy-efficient antenna solutions. These results advance the development of compact, highly efficient antennas for future advanced wireless communication applications.

Keywords: 5G, Patch Antenna, MIMO, 3.5GHz, Isolation, DGS

1. INTRODUCTION

The origin of patch antennas dates back to the 1950s.Georges A. Deschamps introduced the concept of the microstrip antenna in 1953, but the practical applications of this idea remained limited due to the lack of suitable dielectric materials and manufacturing techniques. Research into microstrip antenna technology gained momentum in the 1970s. In 1972, Robert E. Munson introduced the microstrip patch antenna, demonstrating the practical applications of this structure [1]. These developments paved the way for microstrip antennas to be used in an increasingly wider range of applications.In the 1980s, the fabrication and application of microstrip antennas became widespread, and various feeding methods and patch geometries were developed to enhance performance. Furthermore, during this period, significant theoretical approaches, such as the cavity model used in antenna analysis, were introduced to the literature [2,3].

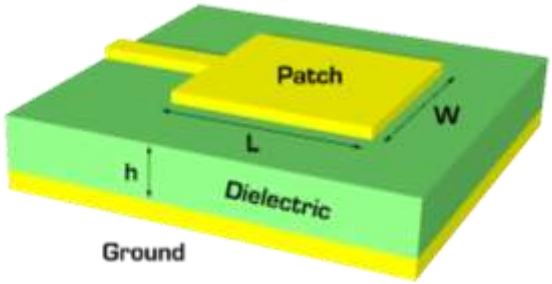


Figure 1: Patch Antenna Board Diagram

A patch antenna, also commonly known as a microstrip antenna, is a type of antenna characterized by a low-profile and planar structure. A patch antenna consists of three main components [4]:

1) The Patch: This is a radiating element made of a conductive material (typically copper). Its dimensions determine the antenna's resonant frequency.

2) The Dielectric Substrate: This layer is situated between the patch and the ground plane. Its dielectric constant (ε_r) and thickness affect the antenna's electrical size and bandwidth. Common materials used include FR-4, Rogers RT/Duroid, and Taconic.

3) The Ground Plane: This is a conductive plane that forms the backdrop of the structure. It provides an electrical return path and contributes to the directionality of the electromagnetic waves.

In order to utilize the capabilities offered by technology in the most efficient way, it is crucial to optimize the fundamental performance parameters of antennas, particularly in terms of bandwidth, directivity, and gain. Consequently, microstrip patch antennas have emerged as one of the prominent antenna types in 5G communication systems due to their compact structure, low profile, ease of fabrication, and adaptability.

MIMO (Multiple-Input Multiple-Output) systems are an ideal solution for meeting the high-performance expectations of 5G and effectively utilize multiple antenna elements for this purpose. The close proximity of these antennas causes mutual coupling, which negatively impacts system performance. Therefore, a high degree of isolation between the antennas is a key design objective [5,6].

One of the most significant challenges encountered in such systems is to improve overall system performance by increasing isolation and reducing mutual coupling, which arises from the close

placement of antenna elements. Techniques such as Defected Ground Structure (DGS) are employed to mitigate mutual coupling between antenna elements and ensure maximum performance [7,8]. DGS refers to structures implemented on the ground plane of microstrip antennas. These structures enhance antenna performance by modifying the current distribution and creating stopbands at specific frequencies [9]. Typically designed by introducing slots or voids in the ground plane, DGS is a critical element for MIMO systems, especially in 5G applications. DGS improves the isolation and overall performance of the antenna system because it disrupts the surface current paths, enabling the suppression of unwanted modes and the reduction of mutual coupling [10,11].

This study focuses on the analysis of the enhanced performance, particularly the isolation and DGS system, of a 5G MIMO patch antenna designed to operate in the 3.5 GHz frequency band. The design aims to develop a high-performance and easily integrable antenna solution that can be used specifically in urban applications. In this context, the conducted work aims to contribute to suitable antenna structures for 5G technology and serve as a reference for future communication systems.

2. ANTENNA DESIGN

2.1. Patch Antenna Dimensions

Microstrip antenna design fundamentally depends on parameters such as the resonant frequency, dielectric constant, substrate thickness, and patch dimensions. The first step in our study was to determine the operating frequency of the antenna. For this design, a resonant frequency of 3.5 GHz was targeted for 5G applications."Since the selection of the dielectric material directly affects the electromagnetic properties of the antenna, the widely used FR-4 material was chosen for this purpose. The dielectric constant of this material is set as ε_r = 4.3, and the substrate thickness is set as h = 1.6mm. Furthermore, the speed of light value used in electromagnetic calculations is c = 3x10^8m/s.

The width of the patch (W) affects the antenna's impedance matching and efficiency [12]. It is calculated using the following formula:

$$W = \frac{c}{2f}\sqrt{\frac{2}{\varepsilon_r + 1}}$$

The **effective dielectric constant**, which is required for the length of the antenna:

$$\varepsilon_{ff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\sqrt{1 + 12\frac{h}{W}}$$

The length of the patch (L) is determined by the resonant frequency, but a correction is applied due to the fringing of the electromagnetic fields at the edges:

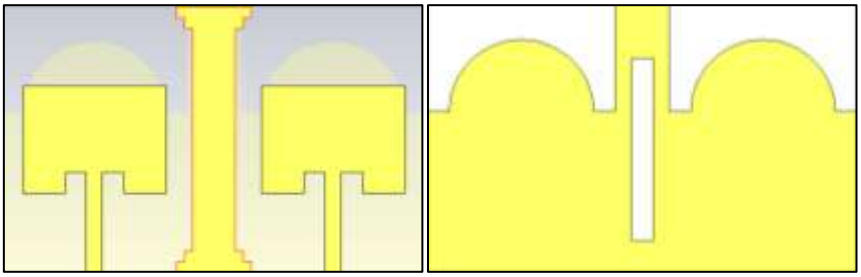
$$L = \frac{c}{2f\sqrt{\varepsilon_{ff}}} - 0.824\ x\ h\frac{(\varepsilon_{ff} + 0.3)(\frac{W}{h} + 0.264)}{(\varepsilon_{ff} - 0.258)(\frac{W}{h} + 0.8)}$$

Consequently, the patch dimensions were determined as W = 27mm and L = 20.3mm.

2.1. Proposed Antenna Design

The designed 1x2 MIMO antenna structure has been optimized to operate at a 3.5GHz operating frequency. The antenna structure consists of two identical microstrip patch antennas

placed side-by-side. The front and rear surface views of the proposed antenna are presented in Figure-2.



(**a**) (**b**)

Figure 2: 2D View of the Proposed Antenna Layout (**a**) Front View (**b**) Back View

The patch antennas positioned on the front side are identical, and an isolation structure has been designed to reduce the mutual coupling (electromagnetic interaction) between them. The dimensional parameters of the associated patch and isolation structures are presented in Figure-3, while the corresponding numerical values for these parameters are provided in the table.

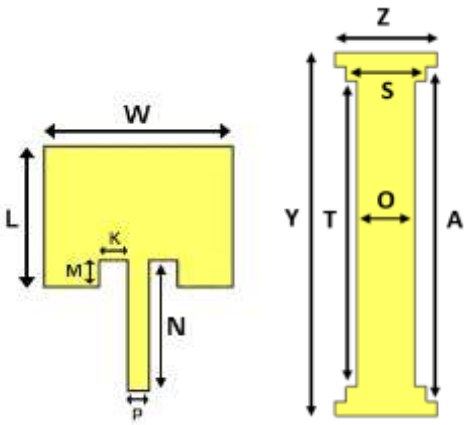


Figure 3: Representation of the Dimensional Parameters for the Patch and Isolation Designs

Table 1: Parameter Values for the Patch and Isolation Designs

Parameters	**Values**	**Parameters**	**Values**
W	27mm	Z	14mm
L	20.3mm	Y	50mm
K	4mm	T	42mm
M	4mm	S	11mm
N	18.9mm	O	8mm
P	3mm	A	46mm

Figure-4 presents the structure on the antenna's ground plane, which consists of two symmetrically etched semi-circular shapes and a narrow rectangular slot positioned in the center. This configuration modifies the path of the surface currents, thereby preventing currents from directly coupling to the adjacent antenna element. Consequently, mutual coupling is reduced, and the overall MIMO performance of the antenna is enhanced.

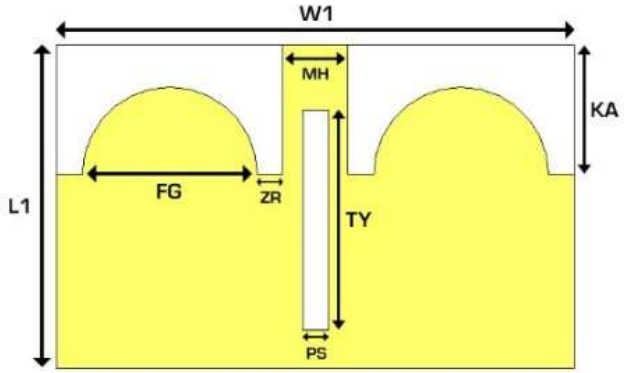


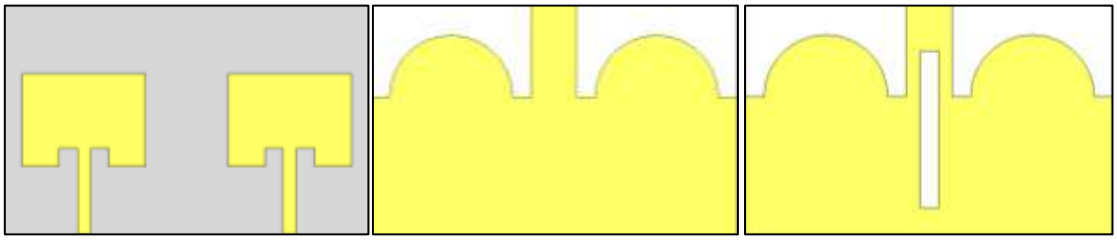
Figure 4: Representation of the Dimensional Parameters for the DGS Design

Table 2: Parameter Values for the DGS Design

Parameters	**Values**	**Parameters**	**Values**
W1	80mm	TY	34mm
L1	50mm	PS	4mm
FG	27mm	KA	20mm
MH	10mm	ZR	4mm

3. IMPLEMENTATION AND SIMULATION

This section presents the optimization studies performed to reach the proposed configuration of the designed 5G 1x2 MIMO. The study separately examines the performance of two distinct isolation techniques applied to the antenna's front surface and two different DGS configurations implemented on the rear-side ground plane, followed by a comparative analysis using graphical results.



(**a**) (**b**) (**c**)

Figure 5: Steps of DGS Design (**a**) Front View (**b**) View of DGS-1 (**c**) View of DGS-2

In the first phase of the design, the simple front surface structure shown in Figure 5 was kept constant. Subsequently, two DGS geometries were designed on the back ground plane to reduce the mutual coupling between the elements. The resulting $|S_{11}|$ (Return Loss) and $|S_{21}|$ (Isolation Loss/Coupling Loss) graphs obtained from the simulation are presented below.

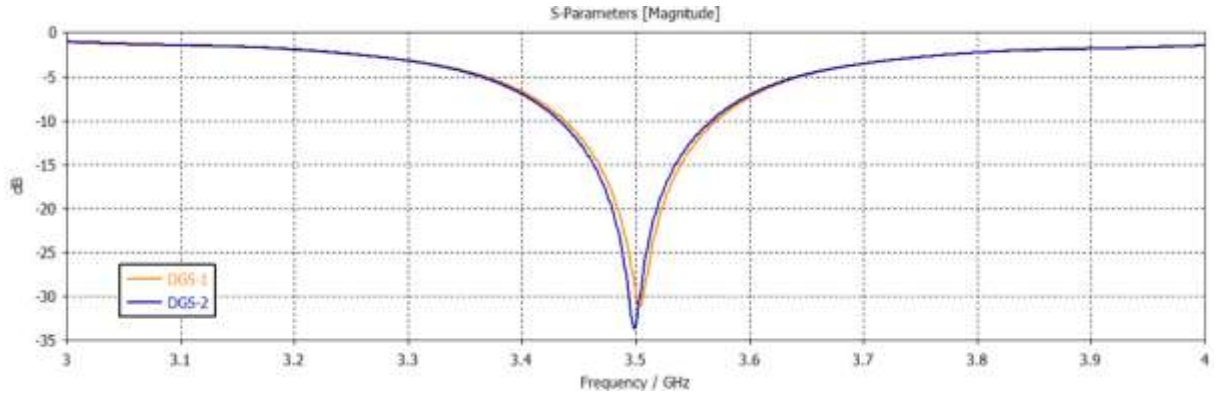


Figure 6: DGS Simulation S_{11} Graph

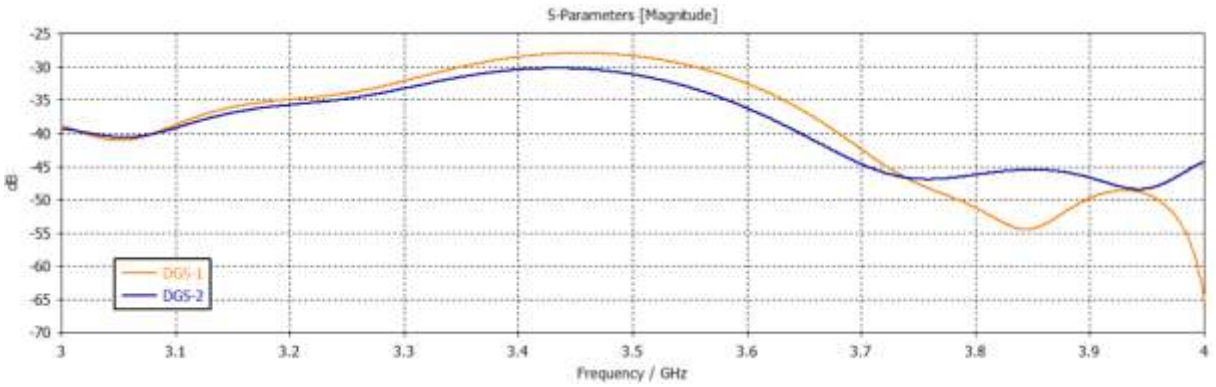
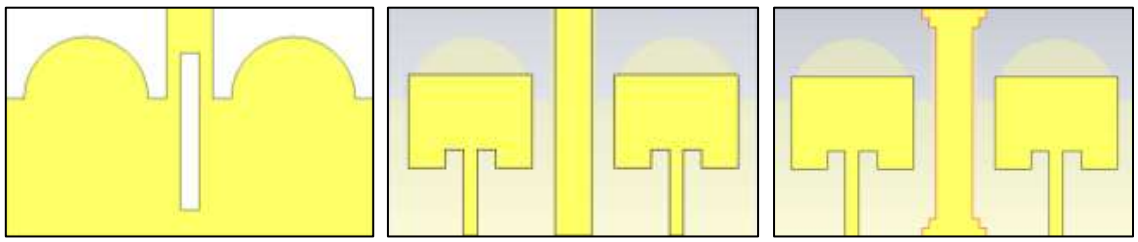


Figure 7: DGS Simulation S_{21} Graph

Table 3: Simulation Results of DGS

Antennas (DGS)	$\|S_{11}\|$	$\|S_{21}\|$
DGS-1	-29.61	-28.33
DGS-2	-33.27	-31.14

Observing Figure 6, the $|S_{11}|$ value for the DGS-2 configuration at the 3.5GHz operating frequency demonstrates superior impedance matching compared to DGS-1, reaching -33.24dB. Furthermore, in Figure 7, the $|S_{21}|$ value of -31.12dB for DGS-2 clearly reveals its enhanced effectiveness in reducing the mutual coupling between the antennas when compared to DGS-1. Consequently, the DGS-2 design proved to be the most optimal DGS configuration.



(**a**) (**b**) (**c**)

Figure 8: Steps of Isolation Design (**a**) Back View (**b**) View of Isolation-1 (**c**) View of Isolaiton-2

In this phase, with the DGS structure (Figure 5(**c**)) determined in the previous section held constant, studies were conducted to further enhance the isolation performance between the two patch antennas on the front surface. The isolation study involved a comparison between configurations achieved by placing metallic strips (or lines) between the antennas. Two different isolation structures were simulated in terms of their $|S_{11}|$ and $|S_{21}|$ parameters, and the resulting graphs are presented below.

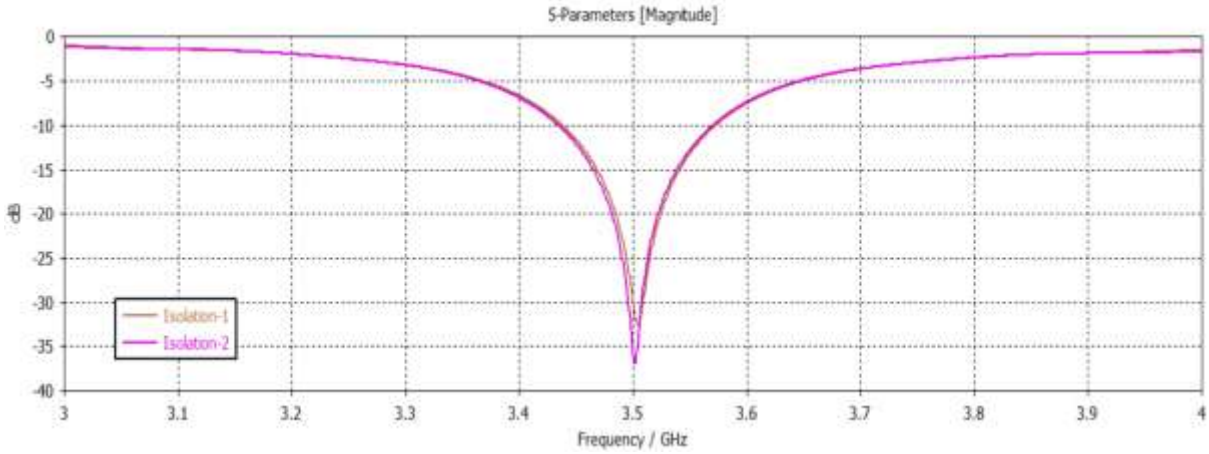


Figure 9: Isolation Simulation S_{11} Graph

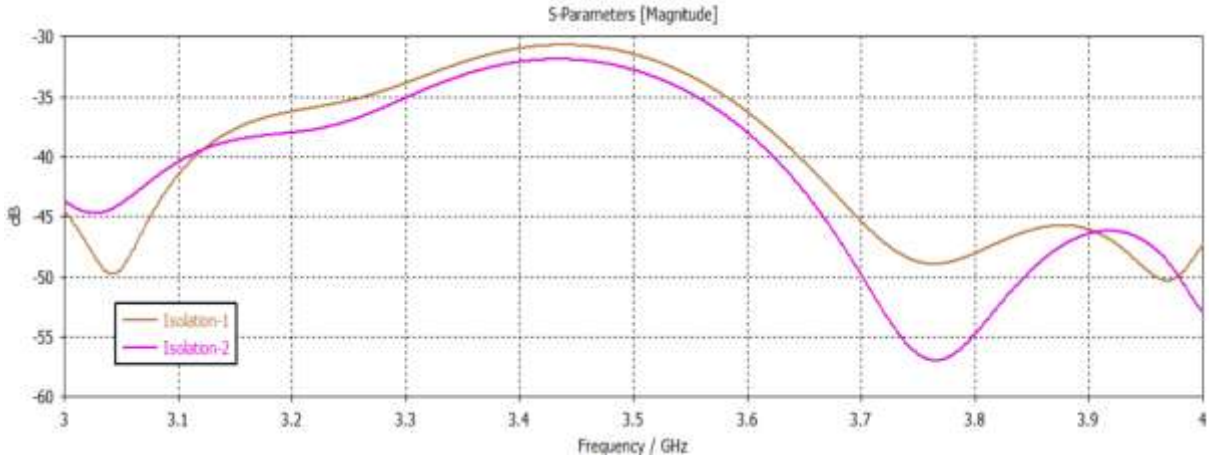


Figure 10: Isolation Simulation S_{21} Graph

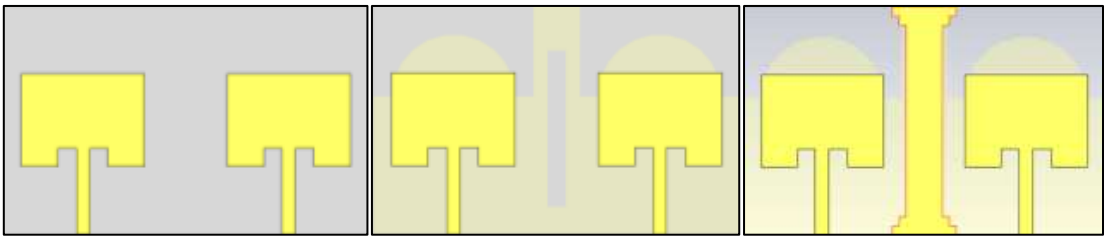
Table 4: Simulation Results of Isolation

Antennas (Isolation	$\|S_{11}\|$	$\|S_{21}\|$
Isolation -1	-29.91	-31.45
Isolation -2	-35.94	-32.77

When comparing the results of the isolation studies, a significant performance enhancement was observed in the $|S_{21}|$ parameter for the Isolation-2 structure presented in Figure 8(**c**). This demonstrates a substantial reduction in the mutual coupling between the antennas. Despite this improvement, there was only a negligible degradation in the $|S_{11}|$

parameter. Based on the results in the table, the most optimal isolation surface is the one shown in Figure 8(**c**), yielding values of -35.94 dB for $|S_{11}|$ and -32.77 dB for $|S_{21}|$.

For the proposed 1x2 MIMO antenna, the design shown in Figure 5(**c**) constitutes the DGS, while the design in Figure 8(**c**) constitutes the front-side isolation structure. In order to accurately observe the performance increase provided by the selected antenna design, a comparative analysis of the proposed antenna was performed against both the non-isolated version and the version containing only the DGS structure.



(**a**) (**b**) (**c**)

Figure 11: Comparison of the antenna designs (**a**) Base Antenna (**b**) Only DGS (**c**) Proposed Antenna

The resulting $|S_{11}|$ and $|S_{21}|$ graphs, obtained from the comparative analysis of the proposed antenna design (illustrated in Figure 11(**c**)) with the other antenna versions, are presented below.

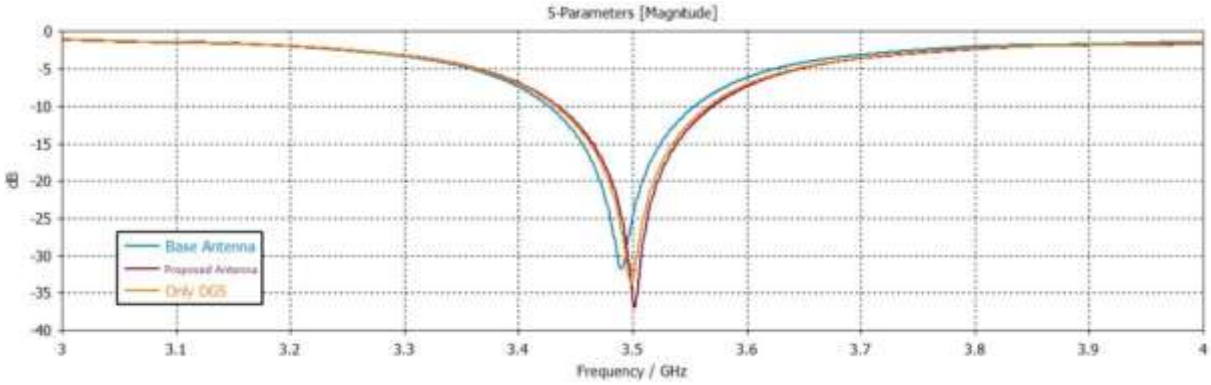


Figure 12: S_{11} Comparison Graph of the Antennas

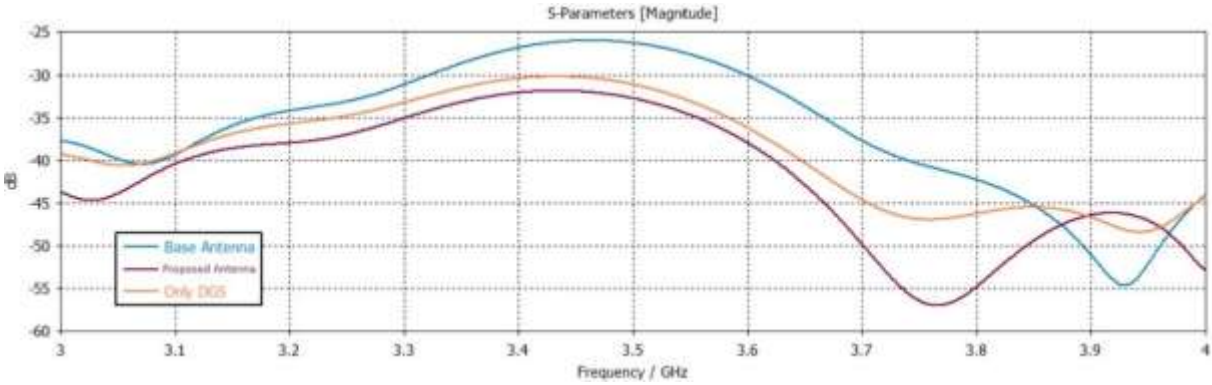


Figure 13: S_{21} Comparison Graph of the Antennas

Table 5: Simulation Results of The Antenna Designs

Antennas	$\|S_{11}\|$	$\|S_{21}\|$
Base Antenna	-24.62	-26.28
Only DGS	-33.27	-31.12
Proposed Antenna	-35.94	-32.77

The simulation results demonstrate that the designed proposed antenna, which incorporates both the DGS and the isolation structures, has yielded a remarkable improvement in the antenna's performance parameters at the 3.5GHz operating frequency, achieving values of up to -35.94 dB for $|S_{11}|$ and up to -32.77 dB for $|S_{21}|$.

A comparison of the 1x2 MIMO Antenna design with relevant antenna designs found in the literature is presented in the Table 6.

Table 6: Comparison with Similar Studies in the Literature

Reference	**Dimensions(mm)**	**Freq.(GHz)**	**Dielectric**	**S_{21} (dB)**
[13]	60x160	3.58	FR-4	-24.9
[14]	133x70	2.45/3.5	Felt Textile	-30
[15]	66x45	2.21/6	AGH4-Melinex	≤-15
[16]	100x50	3.5	Rogers 5880	-33.21
This Study	**80x50**	**3.5**	**FR-4**	**-32.77**

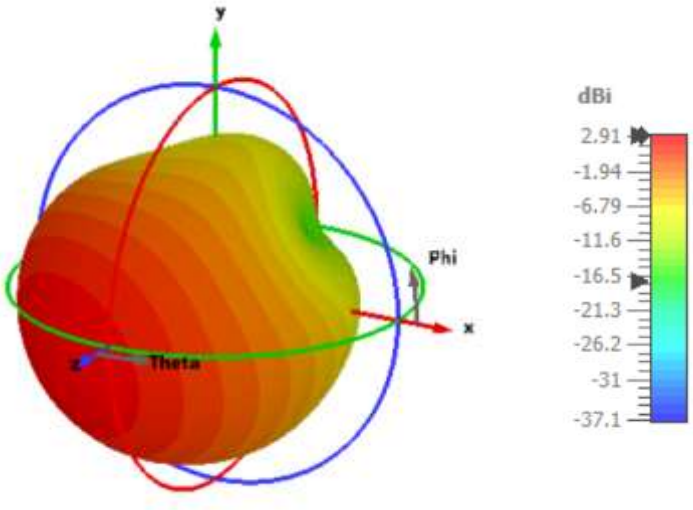


Figure 14: 3D View of Far-Field Gain Radiation Pattern

The 3D graphical values show that the designed antenna has a gain of 2.9dBi. This result, combined with the performance of our antenna, demonstrates an efficient antenna structure.

4. CONCLUSION AND COMMENTS

In this study, a 1x2 MIMO 5G antenna design was successfully realized. Both DGS and isolation structures were utilized to enhance the antenna's performance. The simulation results

demonstrated that the antenna achieved $|S_{11}|$ and $|S_{21}|$ values of -35.94 dB and -32.77 dB, respectively, at the 3.5GHz operating frequency. Furthermore, the design exhibited a gain of around 2.9 dBi and the design's compact dimensions of 80x50 offer a significant advantage for the small-sized, high-performance, and energy-efficient antenna solutions required by 5G technology. The findings will contribute to the development of compact and highly efficient antennas suitable for use in future advanced wireless communication applications.

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MECHANICAL BEHAVIOR OF THE INTERFACE IN THE INDUSTRIAL JOINING OF CFRP – METAL HYBRID STRUCTURES

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ABSTRACT

Adhesive-based joining methods are widely used for metal-composite hybrid structures in the defense and aerospace sectors to meet the demands for lightweight and high strength. This study investigated the bonding of AA7075-T6 alloy aluminum plate to carbon fiber-reinforced epoxy matrix composite (CFRP) plates using adhesive film, and the effects of different surface preparation processes on the interfacial bond strength. Various mechanical and chemical surface preparation processes, such as glass-sand blasting, anodizing, and cross-marking, were applied to the surfaces of the aluminum plates. The CFRP plates were prepared to dimensions in accordance with the ASTM D1002 standard and then bonded to the aluminum plates with an epoxy-based adhesive film. Shear tests were applied to the prepared samples. Precision cutting was then performed for metallographic examination, and the samples were embedded in Bakelite. Optical microscope analyses were performed. The results showed that glass-sand blasting and anodizing provided significantly higher shear strength at the AA7075-T6/CFRP joint interface compared to other surface preparation methods. However, a significant decrease in bond strength was observed on cross-ribbed surfaces. The study demonstrates that AA7075-T6 alloy can be used effectively in high-performance hybrid bonds with CFRP structures with appropriate surface preparation methods.

Keywords: CFRP, AA7075-T6 , Adhesive, Surface Treatments, Shear Strength

1. INTRODUCTION

The use of lightweight materials with high specific strength has been increasing since the 1940s to increase energy efficiency and maximize performance in the aerospace, defense, and automotive industries. Advances in composite material technology, particularly in recent years, have expanded the use of polymer matrix composites (CFRP) in structural elements. However, in industrial applications, it is not always possible for a single material group to meet all design requirements such as ductility, toughness and impact resistance. Therefore, the design of "hybrid structures", which combine the ductility and toughness of metals with the lightweight and high strength properties of composites, plays a critical role in engineering [1-3].

The biggest challenge in the production of hybrid structures is the reliable joining of these materials (metal-composite), which have completely different physical and chemical properties. Conventional mechanical joining methods (riveting, bolting) cause stress concentrations, fiber ruptures, and increased weight in composite structures, while welding methods have limited applicability due to material incompatibilities [4-7]. Adhesive bonding, in this context, stands out as a strong alternative to mechanical joining because it allows materials with different properties to be joined, provides uniform stress distribution, increases corrosion resistance, and provides lightweight construction. [8-12].

The mechanical behavior and durability of adhesive joints depend largely on the interface properties between the surfaces joined by the adhesive. Failure mechanisms that can occur at the interface can occur as adhesive, cohesive, or mixed failure. The joint areas are subjected to various types of stresses, such as tension, compression, shear, separation, and peeling. Figure 1 illustrates the different types of loads that can occur on the adhesive joints. These joints can support each of the specified loads individually or can withstand the combined application of multiple loads [13, 14]. Especially in the joining of aerospace-grade aluminum alloys such as AA7075-T6 with CFRP, the structure of the natural oxide layer on the aluminum surface and surface roughness are factors that directly affect bond strength. Studies in the literature on the problems encountered in determining the mechanical properties of adhesives and ensuring reproducibility emphasize the critical importance of surface preparation processes [15]. Various mechanical and chemical treatments such as sandblasting, acid etching, and anodizing are applied to increase the surface energy and ensure mechanical locking [16].



Figure 1. Different types of loads in the area of the adhesively bonded sections [10]

Öztürk [17], in their study on AA7075-T6 aluminum alloys, investigated the effects of surface roughness and surface free energy on bond strength and reported that hybrid etching methods increased strength. Similarly, Çakır and Kınay [18] investigated the effects of surface treatment and overlap length on mechanical properties in joining aluminum and glass fiber composites. However, comparative studies on the effects of different surface treatments (especially combinations of anodizing and sandblasting) on interfacial shear strength in AA7075-T6 and CFRP hybrid structures, particularly in industrial applications, using "film adhesives" to stabilize adhesive thickness, are rarely found in literature.

This study addresses the bonding of AA7075-T6 aluminum alloy, widely used in the aerospace and defense industries, with Carbon Fiber Reinforced Polymer (CFRP) composite plates using an epoxy-based structural film adhesive. Three different surface treatments were applied to the aluminum surfaces: mechanical abrasion (cross-hatchting/Al-Cross), silica sand blasting (Al-Sandb), and glass sand blasting followed by anodizing (Al-Coating). Lap-shear tests were applied to the produced hybrid samples in accordance with ASTM D1002, and the mechanical behavior of the interface was investigated.

2. MATERIAL AND METHOD

2.1. Materials

In this research, hybrid structures formed by the joining of aluminum alloy (AA7075-T6) and CFRP materials via a Solvay MTA 240 epoxy-matrix adhesive were analyzed.

2.1.1. Aluminum plate (AA7075-T6)

This study aimed to improve the bonding performance of 7075 aluminum alloy, a frequently used material in the aerospace industry. Three different surface configurations were tested on aluminum specimens measuring 100x25x3 mm to optimize bond strength with the CFRP structure. Three specimens were used for each process type.

2.1.2. Pre-preg carbon fabric

The fabric plies were oriented in a balanced, symmetrical pattern. A total of 10 fabric layers were used to create a 2.7 mm thick sheet. The layer orientations were laid at 0°/45°/90°/-45°/0°/0°/-45°/90°/45°/0°. During the laydown, a vacuum was applied every other layer and held under vacuum for 5 minutes. Twill weaving was preferred because the composite provides equal strength in all directions.

2.1.3. Adhesive film

Epoxy-based Solvay MTA 240 Adhesive Film (MTA240/PK13-313g/m²) was used to bond the metal and composite. This adhesive was selected because it is suitable for use on both metal and composite surfaces and its pre-impregnated film structure ensures that the adhesive amount can be applied equally to all specimens during bonding.

2.2. Bonding Operation

Surface preparation is the most critical element in bonding processes, followed by curing procedures. This study aimed to create a bond between epoxy resin-based carbon fiber-reinforced composite panels and metal materials using an adhesive film containing an epoxy resin matrix. To achieve this goal, various pretreatments were applied to metal surfaces, and the effects of these treatments on bonding performance were investigated. The bonded areas of the composite panels were subjected to a surface abrasion treatment, measuring 12.5x25 mm and then all specimens were cleaned with alcohol. The areas outside the bonding area were covered with high-temperature-resistant masking tape. After the cleaning process was completed, the specimens were then bonded using the adhesive film. Figure 2 shows the bonded plates.

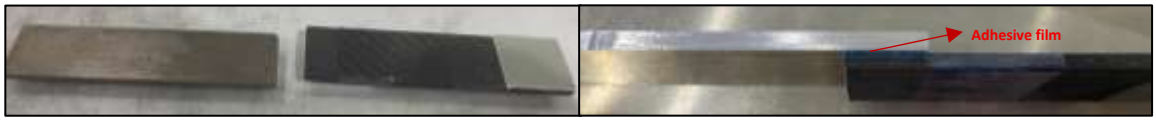

Figure 2. Joined composite-metal plates

2.3. Shear Test

The universal testing machine Instron 8503 (500 kN) was used in the tests. The tensile speed was 1.3 mm/min, as specified in the ASTM D1002 standard. The highest results for aluminum specimens after the shear test were observed in samples treated with glass sandblasting and anodizing (Al-Coating), while the lowest strength values were recorded for the specimens featuring cross-hatching patterns (Al-Cross). The resulting interfaces after the lap-shear tests are displayed in Figures 3a and 3b**.**

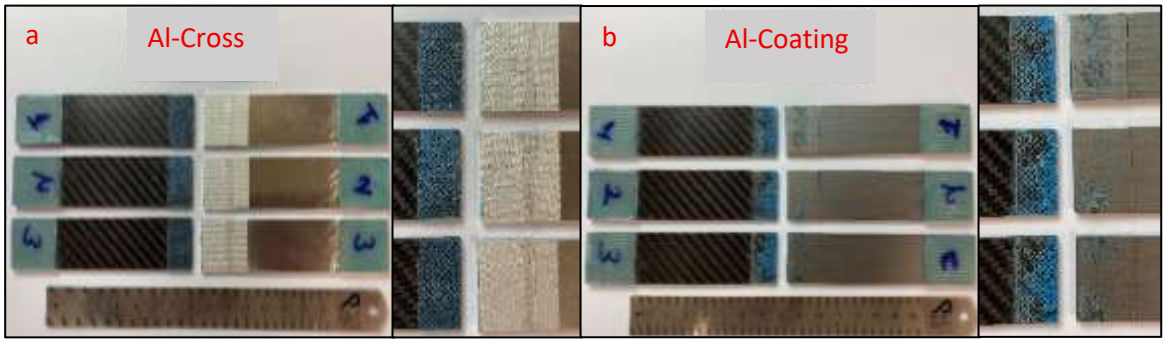

Figure 3. Visual representation of the AA7075-CFRP specimen following the shear test **a)** Al-Cross **b)** Al-Coating

2.4. Characterization

For metallographic examinations, the specimens were embedded in bakelite and subsequently subjected to grinding and polishing procedures. On the prepared specimens, investigations of the interfacial bond formed between the composite and the metal after the shear test were conducted. For these investigations, the 10x15 mm bakelite-mounted specimens were examined using an inverted optical microscope.

3. EXPERIMENTAL RESULTS

Inverted microscope images illustrating the interfacial bond between the residual adhesive and the metallic surface, following the lap-shear test of the Aluminum/CFRP specimens, are presented in Figures 4a, 4b, and 4c. In these images, the regions colored black represent the CFRP, the white regions correspond to the aluminum, and the intermediate, relatively gray regions belong to the adhesive.

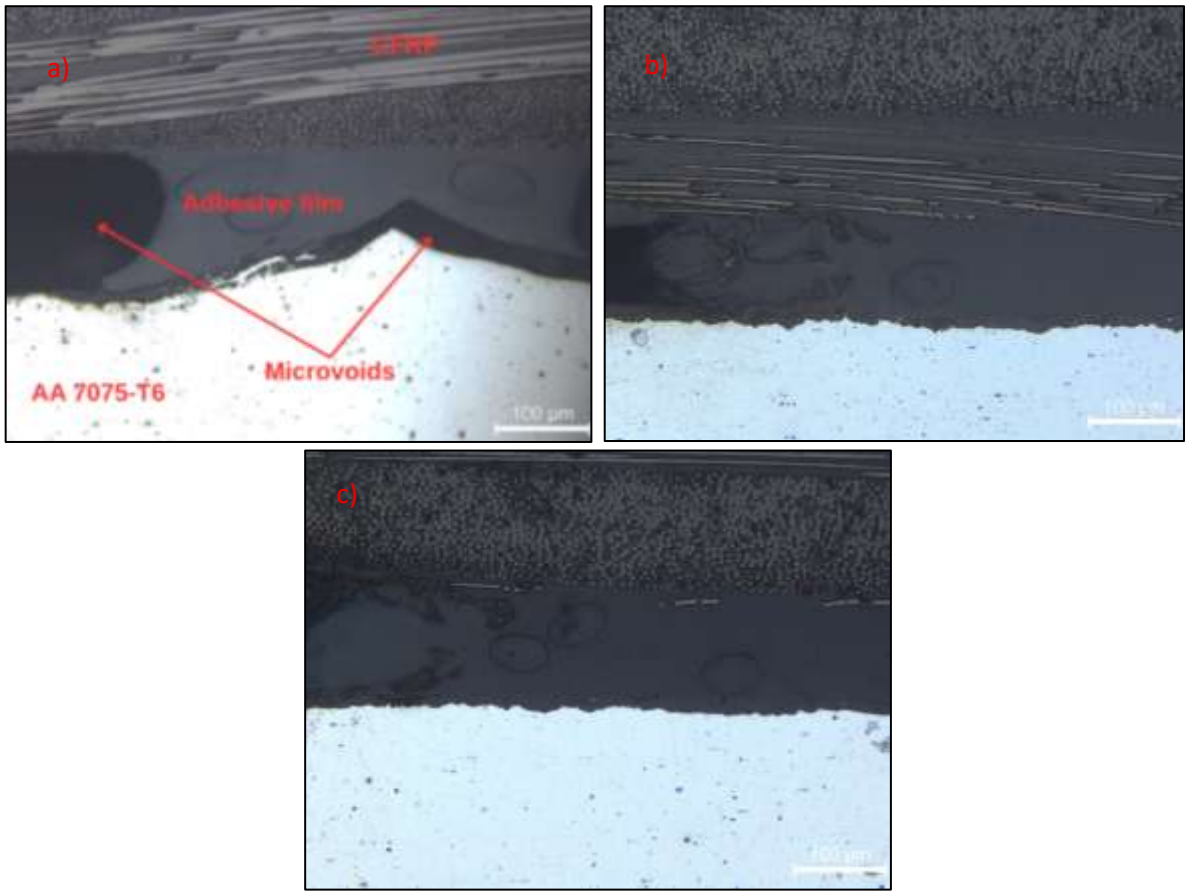

Figure 4. a) Cross-hatching patterns (Al-Cross) **b)** Sandblasting with silica sand (Al-Sandb) **c)** glass-blasting combined with anodization (Al-Coating)

In the AA 7075 specimen where cross-hatching patterns were created, regions featuring deep indentations and protrusions, burrs, and notches (or cracks) are observed on the metallic material, resulting from the material removal process during the formation of these patterns. Especially, this morphology suggests that the deformed adhesive film lacked sufficient thickness, and consequently enough volume, to effectively fill the deep recesses located particularly at the peak regions of these marks. This condition resulted in excessive micro-voids and adhesion deficiencies. Furthermore, it was observed that the adhesive was completely absent in some regions, while residual adhesive was only located within the recessed areas, accompanied by voids (Figure 4a). The very low level of adhesive presence at the end sections of the resulting traces is clearly reflected in the shear test results given in Figure 5. The cross-geometric roughness can cause stress concentrations, making it difficult for the adhesive to fully wettability or mechanically lock onto the surface.

The Al-Sandb sample exhibited a much rougher surface than the other samples. High surface roughness accompanies plastic deformation of the matrix, resulting in greater fracture energy consumption. Several areas of voids are observed between the samples and the adhesive (Figure 4b).

In this study, the adhesion strengths, the interfacial bonds between the materials, and the effects of mechanical and chemical abrasion surface treatments on the adhesion strength of the specimens were investigated. The lap-shear test graph for the specimens is provided in Figure 5. As observed, the highest strength value among the specimens was recorded for the Al-Coating specimen, which underwent glass-blasting combined with anodization, at 15.77 MPa,

while the lowest strength value of 7.30 MPa was found in the Al-Cross specimen featuring cross-hatching patterns.

In the sample, which called Al-Coating, the surface roughness profile was observed to be more stable and contain fewer pits than the Al-Sandb sample. The depth of the roughened area was observed to be greater compared to the other samples. It was also observed that the adhesive thickness and density were more dense between the two materials (Figure 4c). This indicates that the interfacial bond between the samples will be strong. It is believed that increasing the surface roughness and creating traces in different directions will be beneficial in future studies.

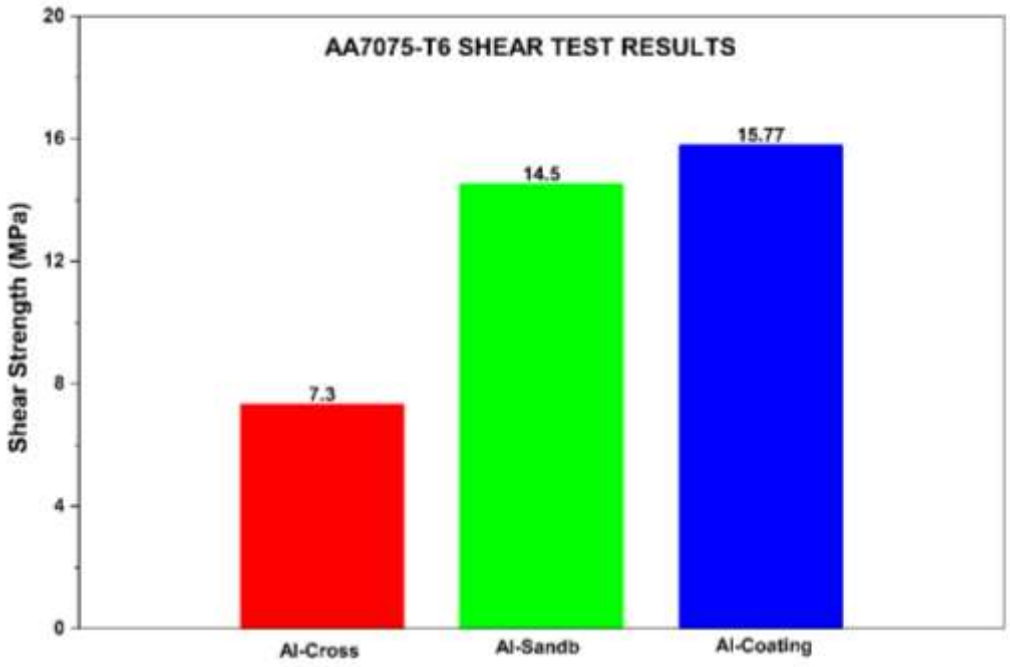

Figure 5. Effect of metal surface treatments on joint shear strength

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FABRICATION OF OPEN-CELL ALUMINA CERAMIC FOAMS VIA THE REPLICA METHOD

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ABSTRACT

Metallic and ceramic foams are divided into two basic classes based on their pore structure: closed and open pore. Differences in cell structure are directly related to the manufacturing method and the parameters used. Open-pore foams, due to their large specific surface area, are preferred in heat exchangers. Ceramic foams, due to their high liquid/gas permeability and corrosion and high temperature resistance, are preferred in filtration and separation processes, and in water treatment applications where unwanted ions can be removed from solution. In this study, open-cell Al-based alumina ceramic foams with varying pore sizes were fabricated using the powder metallurgy method combined with aluminum powder and the polyurethane foam (PU) replication technique. The structure obtained after the removal of the PU at 500°C 3 hours was subsequently sintered in an open atmosphere for 6 hours at temperatures of 850°C, 900°C, and 950°C. X-Ray diffraction (XRD) analyses, scanning electron microscopy (SEM) and microstructural investigations were performed on the fabricated ceramic-coated foams. During the high-temperature oxidative sintering process conducted in an open atmosphere, alumina ceramic-coated foams with optimal properties were successfully obtained at 950 °C, achieved through the sintering mechanism resulting from the oxidation of the aluminum powders.

Keywords: Open-cell foam, Powder metallurgy, Metallic foam, Ceramic foam

INTRODUCTION

Advanced porous metallic and ceramic materials have played a critical role in industrial applications in recent years, owing to their unique combination of physical and thermal properties. Key advantages that distinguish these materials include characteristics such as high specific surface area, low density, chemical stability, and thermal shock resistance [1-3]. Ceramic foams, which are classified as open-cell or closed-cell based on their pore morphology, are primarily utilized in environments characterized by demanding conditions, such as molten metal filtration, catalyst support units, heat shields, and biomedical implants. [4-7]. In contrast to metallic foams, ceramic foams offer oxidation resistance and dimensional stability at elevated temperatures. Specifically, open-cell ceramic foams maximize heat and mass transfer by generating turbulent flow, owing to their interconnected pore networks that allow fluid permeability. [8]. Studies have focused on various ceramic materials such as silicon carbide (SiC), zirconia (ZrO_2), and alumina (Al_2O_3). Among these, alumina stands out for its high melting point, mechanical strength, and cost-effectiveness. [9]. Although various techniques such as "direct foaming" and "gel casting" are used in the production of ceramic foams, the polymer sponge replica method developed by Schwartzwalder and Somers is the most widely accepted technique on an industrial scale [10]. This method is based on the principle of impregnating a flexible polyurethane foam (PUF) with a ceramic slurry, removing the excess slurry, and subsequently sintering the ceramic structure by burning out the organic scaffold via applied thermal treatments. A representation of the structure obtained after the removal of the organic-based template material is provided in Figure 1.

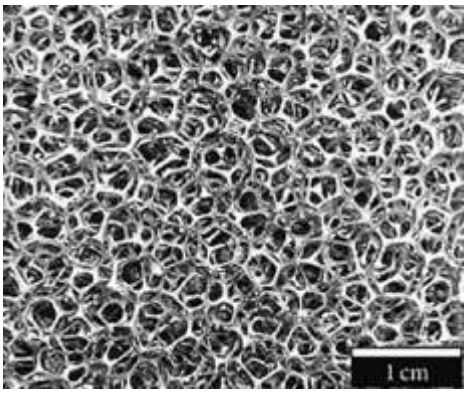

Figure 1. Open-cell metallic foam [11]

The biggest advantage of the method is that the pore structure of the starting polymer can be almost exactly copied into the final ceramic product. [12]. Recent studies have demonstrated that the fundamental challenge in ceramic foams fabricated via the replica method is optimizing the inverse correlation between mechanical strength and porosity. Betke et al. [13], investigated the influence of mixture composition on cellular alumina, while other researchers focused on the effect of the sintering temperature on microstructural defects [14]. However, while the effect of the sintering temperature on the microstructural evolution during the production of alumina-based ceramic foams is known, studies focusing specifically on the liquid phase mechanisms formed within the matrix during the sintering process and the interaction of this phase with the alumina grains are limited. The presence of the liquid phase has a significant role on the densification behavior and grain growth of the ceramic skeleton, and a detailed understanding of this mechanism is needed. [15-18]. The objective of this study is to investigate the physical changes and microstructural characteristics of open-cell pure aluminum-based alumina (Al2O3) coated ceramic foams, fabricated via the replica method using pure aluminum powder and polyurethane (PU) sponges, with respect to different sintering temperatures.

MATERIAL AND METHOD

2.1. Materials

In the experiments, pure Al powders with 99.9 % purity and a particle size of < 10 µm were utilized. Polyurethane (PU) sponges ($C_{25}H_{42}N_2O_6$) with pore sizes of 10, 20 ve 30 ppi (pores per inch) were selected as the organic template material. Polyvinyl alcohol (PVA) in powder form was used as the binder, and deionized water was employed as the solvent.

2.2. Sample Preparition and Process

The production process of the alumina-coated foams comprises the following stages: slurry mixture preparation, template material impregnation, drying, binder and template material removal, and sintering. During the fabrication of the specimens, the procedure followed the process flow chart presented in Figure 2.

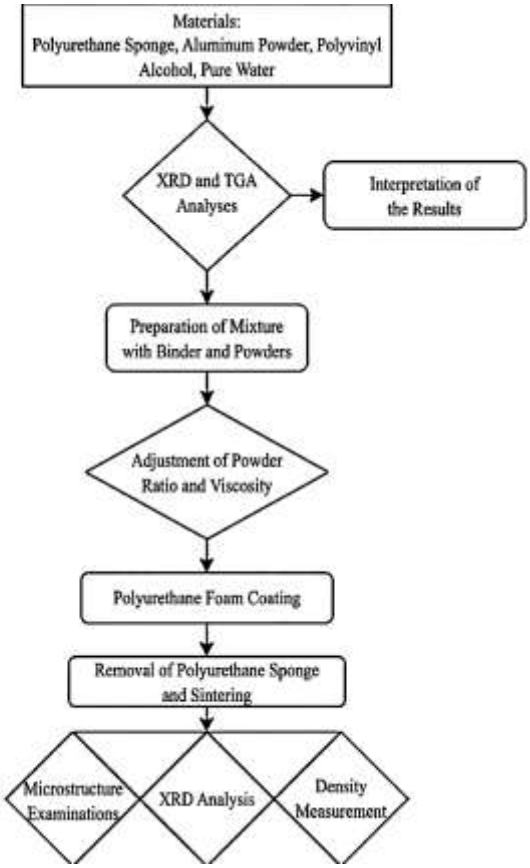

Figure 2. Process flowchart in production

Firstly, a slurry mixture was prepared by mixing deionized water and PVA using a turbula mixer, and the mixture was subsequently allowed to settle for 1 day. Moreover, pure Al powders at a 70% powder ratio determined to be optimal for viscosity, were introduced into this solution, resulting in a mechanically homogeneous slurry. PU sponges with pore sizes of 10 ppi, 20 ppi, and 30 ppi were cut into 20x20x20 mm dimensions using a foam cutting device. The cut sponges were then immersed in the prepared mixture to ensure homogeneous coating. The coated samples were first stored at room temperature for 1 day.

The dried specimens were processed in a furnace under ambient atmospheric conditions for the removal of the binder and template material. Initially, the PVA (binder) was eliminated from the structure at 350°C for 3 hours. Subsequently, the template material (PUF) was removed from the structure by holding the specimens at 500°C for 3 hours. After the template material was removed for the sintering process, the remaining aluminum powders were sintered together at different temperatures (850 °C, 900 °C and 950 °C) under normal atmospheric conditions.

Figure 3 shows the production phase of the samples and Figure 4 depicts the image of the alumina coated metallic foams after the sintering process.

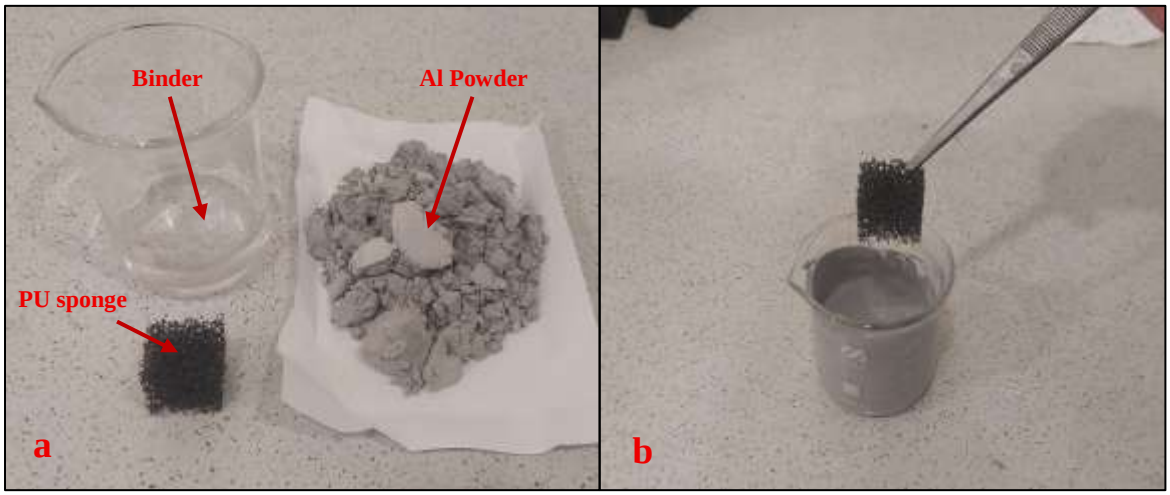

Figure 3. a) Materials which is used when studies **b)** Process for coating the template material with the prepared aluminum slurry.

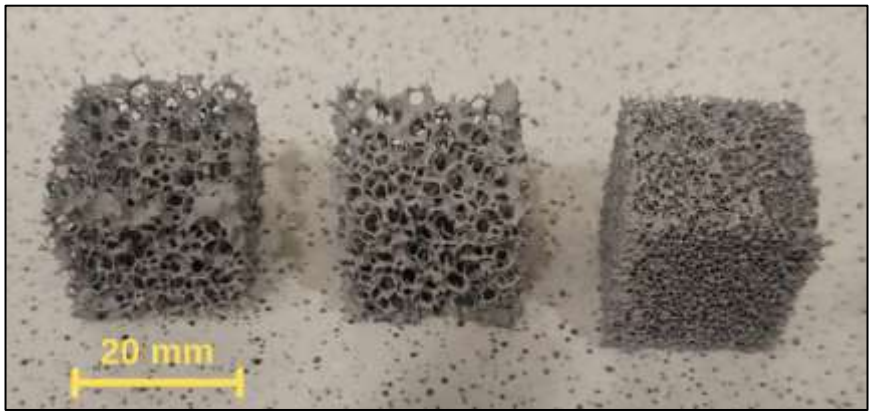

Figure 4. Sintered Al based Al_2O_3 coated foams

5. EXPERIMENTAL RESULTS

Scanning electron microscopy (SEM) analysis of the ceramic foams sintered under open atmospheric conditions was conducted using a JEOL JSM 6060 LV instrument, with the objective of investigating the sintering effects and the morphology of the resulting foam. The SEM micrographs focused on the 20 ppi foam material sintered at 950 °C. As observed in Figure 5a, after the removal of the PU template material, the aluminum powders successfully replicated the shape of the template, effectively forming the cell walls and columns. A micrograph of the fractured surface of the produced foam is presented in Figure 5b. Independent spherical structures formed in various regions on the cell walls are noteworthy (indicated by arrows in Figure 5b). One of these structures is shown at higher magnification in Figure 5c. The Al powders introduced into the structure during the production process are <10 µm in size, which is observable in Figure 5d. The size of these coarse spherical structures formed on the cell walls typically ranges from 50 to 100 µm.

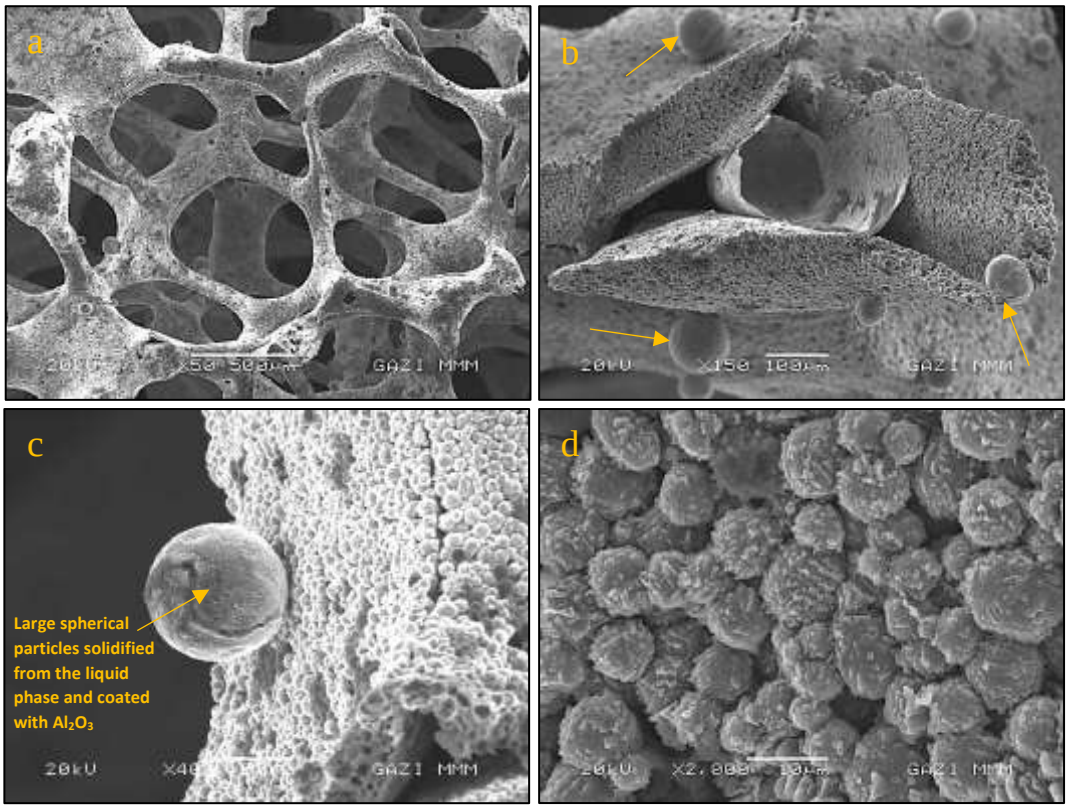

Figure 5. SEM micrographs of the alumina foam sintered at 950°C at different magnifications: **a)** general view, **b)** viewed across the fractured surface, **c)** Solid Al grown in liquid form and coated with alumina and **d)** Initial size alumina coated Al particles

During high-temperature sintering in an open atmosphere, the liquid phase formed in certain sections of the cell walls was observed to migrate towards the surface via capillary action, subsequently forming and solidifying into a spherical shape. The stability of the foam structure, which did not fully transition into the liquid phase or collapse despite the high sintering temperature (950 °C), can be attributed to the rapid and excessive oxidation of the Al particles in the open atmosphere sintering environment, which resulted in the formation of an alumina (Al_2O_3) layer on the powder surfaces. The angular pointed structures clearly visible on the surface of Al powder particles in Figure 5d are oxide structures formed under open atmospheric conditions during the sintering process.

The spherical structures formed in the produced samples were identified as containing dense Al_2O_3, as determined by the XRD analysis given in Figure 6. Generally, peak intensities indicate that the alumina content on Al surfaces increases with increasing sintering temperature. However, the highest alumina content is observed in the XRD analysis of foam sintered at 900°C. This may be attributed to the increased oxidation rate of the sinter medium by leaving the furnace door partially open for a certain period of time. This condition enhances the formation of Al_2O_3 on the surface of the Al powders within the furnace atmosphere.

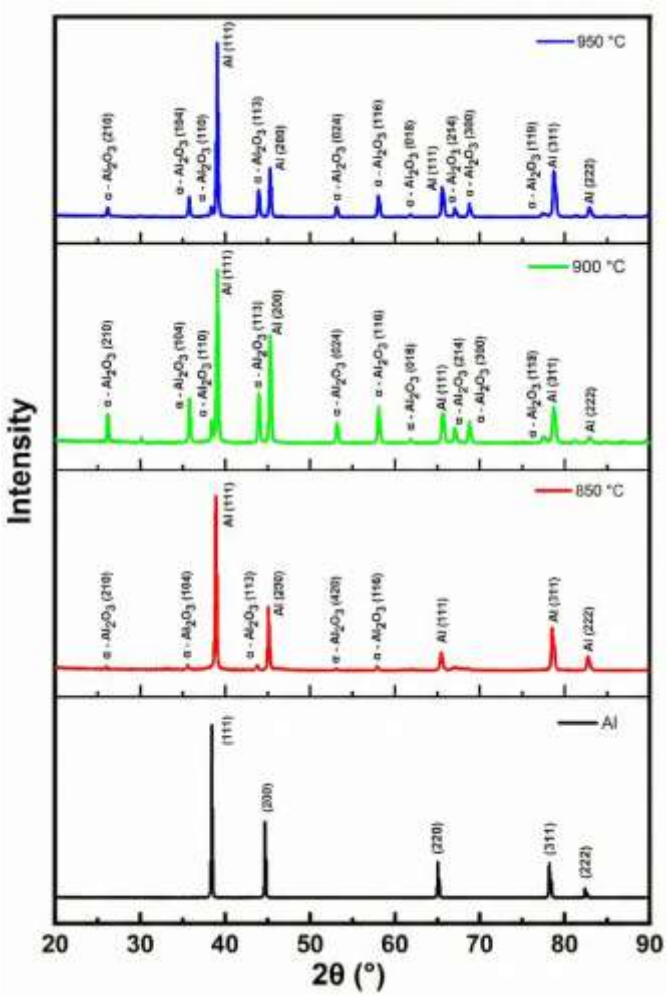

Figure 6. XRD analysis result of pure Al and foams sintered in open atmosphere

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LSI ENDEKSİ İLE KARBON ÇELİK KOROZYON KUPONLARI ARASINDAKİ İLİŞKİLERİN İNCELENMESİ

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ÖZET

Türkiye benzeri gelişmekte olan ülkelerde demir ve çelik sektörü Avrupa ülkelerine kıyasla hala aktif olarak rol oynamaktadır. Demir ve çelik sektörü kendi içerisinde bir çok dinamiği barındırmaktadır metal hurda da bu dinamiklerin en başında karşımıza çıkmaktadır. Türkiye için metal hurdanın önemi Avrupa ve dünya ülkeleri ile karşılaştırıldığında başı çekmektedir çünkü Türkiye'deki demir ve çelik üretiminin %70'e yakını elektrikli ark ocakları ile sağlanmaktadır. Bu durumda metal hurdaların Türkiye'deki kullanımlarında diğer ülkelere kıyasla daha dikkat edilmesi ve önlemler alınması gerektiğini ortaya koymaktadır. Ülkemize yüksek tonajla giriş yapan ve çeşitli ülkelerden gelen bu malzemelerin kontrol edilmesinin gerektiği çok açık ortadadır. Mevcut kontrol mekanizmaları incelendiğinde otomatik bant sistemleri, gözle yapılan çeşitli eksperlik işlemleri karşımıza çıkmaktadır. Bu çalışmada yapay zeka, YOLO V12 gibi görüntü işleme araçları kullanılarak resimler makine öğrenmesi ile sisteme öğretilmiştir.

Anahtar Kelimeler: LSI (Langelier Doygunluk İndeksi), korozyon kuponları, su şartlandırma, su kimyasalları

INVESTIGATION OF RELATIONSHIPS OF LSI INDEX WITH MILD STEEL CORROSION COUPONS

ABSTRACT

Corrosion and scale formation in water systems are significant issues that directly affect the operational efficiency of industrial facilities. One of the most commonly used parameters to monitor these processes is the Langelier Saturation Index (LSI), which predicts the tendency of water to form or dissolve scales. However, since the LSI value is theoretically based on scaling equilibrium, it may not directly reflect the actual corrosion behavior on metal surfaces. This study aims to investigate the relationship between LSI values and metal corrosion rates by employing corrosion coupons in water systems with different chemical compositions. In the experimental study, coupons made of carbon steel were exposed to water environments with varying LSI values for a specified duration. Throughout the testing period, parameters such as pH, temperature, total dissolved solids (TDS), calcium hardness, and alkalinity were regularly measured, and LSI values were calculated accordingly. At the end of the exposure period, the coupons were removed, and corrosion rates were determined through weight loss measurements. The study emphasizes that the LSI should not be considered solely as a theoretical parameter but should be evaluated in conjunction with experimental corrosion observations. Coupon tests under different LSI conditions allow for monitoring corrosion behavior and enable more informed decisions for mitigating corrosion risks in water systems. This approach contributes to the development of effective corrosion management and control strategies in industrial water systems.

Keywords: Langelier Saturation Index (LSI)**,** corrosion coupons, water treatment, water chemicals

INTRODUCTION

The water treatment sector is of great importance all over the world, especially in terms of the efficiency and healthy operation of industrial cooling towers. Cooling towers are very encounter to corrosion due to the appropriate environment inside the cooling tower like the flow of solution that contains dissolved salts, the temperature, the microbiological growth etc [1]. That is why monitoring corrosion in cooling towers is as essential as its occurrence. Corrosion monitoring in industrial cooling towers can be performed using various methods. One is the traditional method, which involves inserting a corrosion coupon and then calculating metal loss. Another is corrosion measurement using online devices. Various institutions market their devices for this technology, but the traditional method was chosen and applied in this study. The most important determinants of the corrosion potential of water include the temperature, pH, dissolved gases, the concentration of sulfate, chloride, and chlorine residual [2]. When all these parameters come together, they reveal the corrosion rate and are linked to the dissolved iron ratio in the systems. Many corrosion monitoring indices are used today. The most commonly used are the Langelier saturation index (LSI) and the Ryznar stability index (RSI). Factors influencing the LSI include pH, total dissolved solids (TDS), temperature, calcium levels, and alkalinity. LSI is a qualitative index that only indicates that the sample in question tends to deposit or corrode. RSI was used to complement LSI and quantify the results. LSI is the most effective indicator for water potential and determination [3]. Formulations made via Excel or some special programs created with the software can be used in LSI index calculations.

MATERIAL AND METHODS

Mild steel corrosion coupons were applied to nine cooling towers constructed at an industrial facility and stored under suitable conditions for two months. Weights were measured before the coupons were installed and then re-weighed using precision scales after their removal.



Figure 1. Mild steel corrosion coupon after placement to the system

Image 1 shows a mild steel corrosion coupon removed from its envelope. The envelope contains the manufacturer's standards. This information is crucial for future calculations. Although the envelopes contain weight information, re-measurement is considered more accurate. All coupons used in this study were taken from unopened envelopes and used in accordance with the standards. The envelopes were opened and the coupons were first visually inspected for any previous corrosion.



Figure 2. Mild steel corrosion coupon placement area

The dark coupon at the bottom of Image 2 is a mild steel corrosion coupon. It is incorporated into the system at the cooling tower return water level. Water flow must be maintained continuously and in direct contact with the coupon; otherwise, measurements cannot yield meaningful data. Measurements taken during periods of excessive cooling tower downtime will also result in similar data issues. Coupons are typically held for two months. Longer holding periods are possible, but frequent checks increase the reliability of the data obtained. Events such as maintenance stops and sudden malfunctions within the facility affect coupon performance. When the system becomes stationary and the corrosion inhibitor is not dosed or circulated, we observe an increase in the corrosion rate. Corrosion rate was calculated in mils per year (mpy) and according to ASTM G1-03 using the formula below [4].

Eql (1) Corrosion Rate = (K x W) / (A x T x D)

where:

K = a constant (see table 1.)

T = time of exposure in hours,

A = area in cm2,

W = mass loss in grams, and

D = density in g/cm3

Table 1. Corrosion rate calculation constant choose [6,7]

Corrosion Rate Units Desired	Constant (K) in Corrosion Rate Equation
mils per year (mpy)	3.45×10^6
inches per year (ipy)	3.45×10^3
inches per month (ipm)	2.87×10^2
millimetres per year (mm/y)	8.76×10^4
micrometres per year (um/y)	8.76×10^7
picometres per second (pm/s)	2.78×10^6
grams per square meter per hour (g/m2 ·h)	$1.00 \times 10^4 \times D$
milligrams per square decimeter per day (mdd)	$2.40 \times 10^6 \times D$

The Langelier saturation index (LSI) is calculated from the values of electrical conductivity or total dissolved solids, calcium, alkalinity, pH and temperature. In practice, the conductivity, pH and temperature are calculated [5]. In conclusion, if we reduce it to its simplest form difference between the actual pH of the solution and pHs calculated [6,7].

Eql (2) LSI = LSI = pHactual – pHs

The Langelier Saturation Index (LSI), which evaluates the tendency of a water sample to either dissolve or precipitate calcium carbonate, is widely utilized as an empirical parameter for assessing water stability [8]. Although LSI is not a direct measure of corrosive activity, it reflects the propensity of water to form or inhibit the formation of a calcium carbonate protective layer. Such a scale layer can provide a physical barrier that limits the contact between water and system components such as pipelines, boilers, and heat-exchange surfaces. In the absence of this protective film, the water is characterized as aggressive, increasing the likelihood of corrosion processes. Highly corrosive water may lead to structural degradation of system elements and can pose public health risks due to the mobilization of lead or other heavy metals [9, 10]. Conversely, excessive scale formation can impair system performance, reduce efficiency, and necessitate maintenance or equipment replacement. The interpretations of both the traditional Langelier Saturation Index (LSI) and the modified LSI proposed by Carrier are derived from the table 2 parameter values [11,12].

Table 2. LSI index parameters [13]

LSI<0	Water is undersaturated with respect to calcium carbonate. Undersaturated water has a tendency to remove existing calcium carbonate protective coatings in pipelines and equipment.
LSI=0	Water is considered to be neutral. Neither scale-forming nor scale removing.
LSI>0	Water is supersaturated with respect to calcium carbonate (CaCO3) and scale forming may occur.

The LSI index and the mpy results of the corrosion coupons were evaluated together to obtain meaningful data.

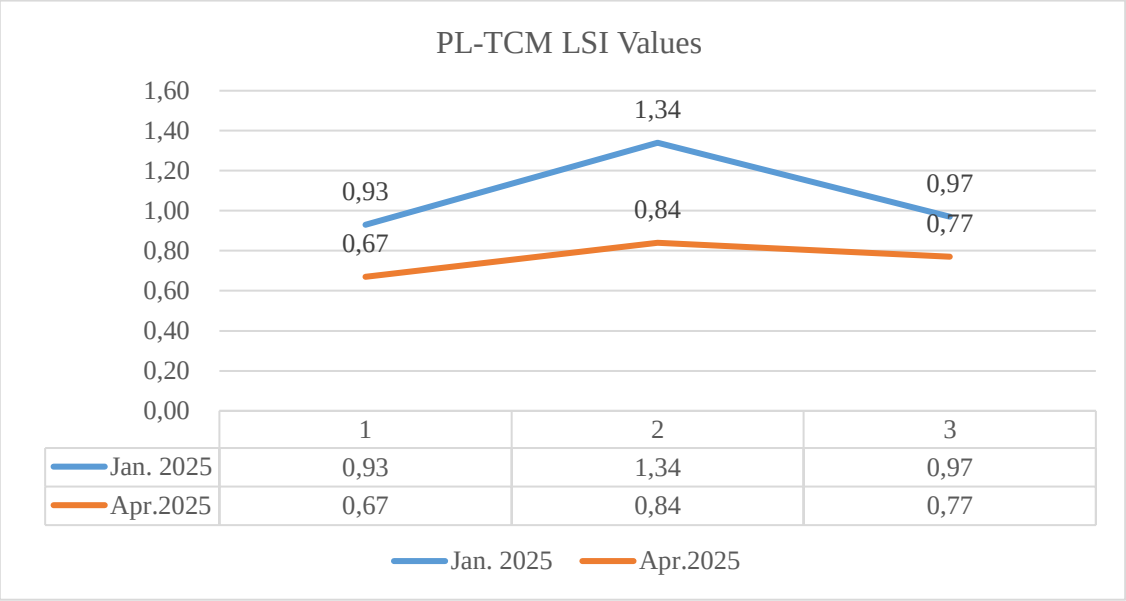

Figure 3. LSI Index of PL-TCM January-April

Chart 1 shows the LSI indices for the cooling tower named PL-TCM for the months of January and April. The corrosion value of this tower was measured as 0.16 mpy in January and 0.10 mpy in April. According to LSI analysis results, there is a tendency for lime formation. According to the corrosion coupon analysis results, there is no corrosive hazard in the tower. The warning about the tendency for scale formation may be due to imbalances in pH and calcium hardness.

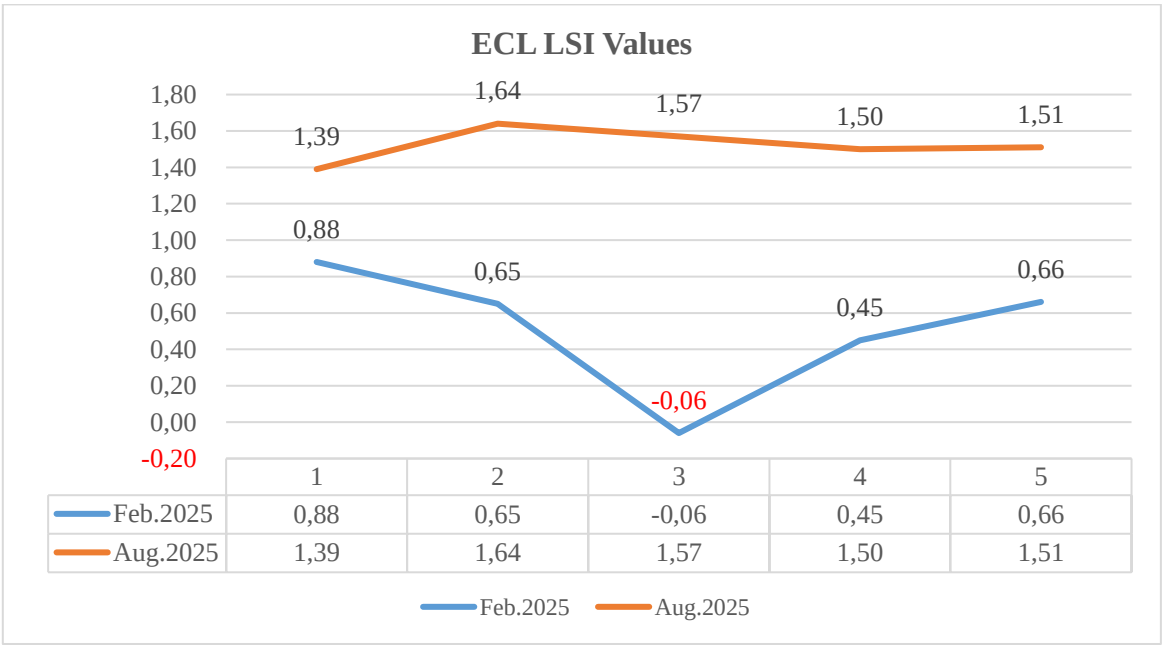

Figure 4. LSI Index of ECL February-August

According to the analysis made on the ECL tower, another cooling tower within the same facility, the LSI data for February and August are given in Chart 2. The corrosion rate value was measured as 0.27 in February and 0.41 in August.

CONCLUSION AND EVALUATION

Although the LSI values in February and August are 90% in favor of scale formation, it is observed that the corrosion rate increases in February.When we examine Graph 2, we see that although February's values are on the scale-forming side, the corrosion rate has increased due to the water shifting to the aggressive side. Because the index only provides a value based on specific parameters, we must make the assessment accordingly. As the sources of hardness in water decrease, the corrosion rate increases accordingly. Although the index calculation provides us with a scale formation, the corrosion rate can never be reset, so an evaluation is necessary. Because hardness in water acts as a natural corrosion inhibitor, the decrease in February caused the corrosion rate in the tower to increase.

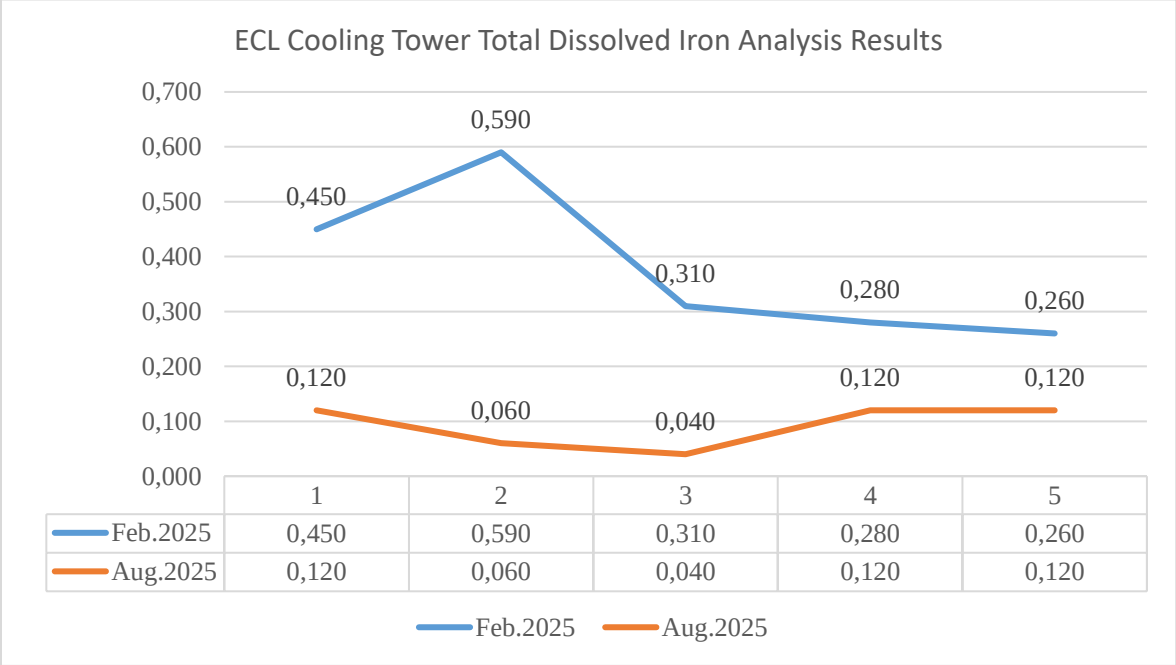

Figure 5. Total dissolved iron test results

Chart 3 shows the total dissolved iron analyses for February and August. Although the LSI values for both months are on the scale, we can say that the LSI values in February eventually reached the neutral side and metal dissolution in the system increased as the water became more aggressive. As a result, the LSI index overlaps with the corrosion rate in the system to a certain extent, and there is even a significant interaction between it and the amount of iron and hardness in the system.

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DEMİR ÇELİK SEKTÖRÜNDE KİMYASAL RİSK ETMENLERİ

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ÖZET

Demir çelik sektörü, hammadde hazırlama, sinterleme, kok üretimi, yüksek fırın prosesleri, çelik üretimi ve haddeleme gibi çok aşamalı ve yoğun kimyasal reaksiyonların gerçekleştiği kompleks bir endüstriyel yapıya sahiptir. Bu süreçler sırasında kullanılan veya yan ürün olarak ortaya çıkan çeşitli kimyasal maddeler, çalışanların maruz kalabileceği önemli mesleki riskler oluşturur. Başta karbon monoksit (CO), kükürt dioksit (SO_2), azot oksitler (NO_x), hidrojen sülfür (H_2S) gibi zehirli gazlar olmak üzere metal oksit dumanları, ağır metal partikülleri, asit-baz çözeltileri, yağlayıcı ve soğutucu kimyasallar ile uçucu organik bileşikler (UOB) sektördeki temel kimyasal tehlikeler arasında yer almaktadır. Bu maddelere solunum, deri teması veya sindirim yoluyla maruziyet; akut zehirlenme, solunum yolu irritasyonu, dermatit, göz tahrişi, merkezi sinir sistemi etkilenimi ve uzun dönemde mesleki astım, kronik obstrüktif akciğer hastalığı (KOAH) ve bazı kanser türleri gibi ciddi sağlık sorunlarına yol açabilmektedir. Bu nedenle kimyasal risk etmenlerinin doğru şekilde tanımlanması, proses bazlı tehlike analizlerinin yapılması, çalışma ortamı ölçümlerinin düzenli olarak gerçekleştirilmesi ve mühendislik kontrollerinin etkin biçimde uygulanması kritik önem taşır. Bunun yanında kişisel koruyucu donanımların doğru seçimi, çalışanlara yönelik sürekli eğitim programları ve uluslararası standartlara uygun kimyasal yönetim sistemleri, sektörde güvenli çalışma ortamı oluşturmanın temel unsurlarını oluşturmaktadır. Bu çalışma, demir çelik sektöründe karşılaşılan kimyasal risk etmenlerini kapsamlı biçimde değerlendirerek, maruziyet kaynakları, sağlık etkileri ve kontrol yöntemleri üzerine bütüncül bir çerçeve sunmayı amaçlamaktadır.

Anahtar Kelimeler: Demir çelik, zehirli gazlar, kimyasal risk etmenleri, sağlık.

CHEMICAL RISK FACTORS IN THE IRON AND STEEL INDUSTRY

ABSTRACT

The iron and steel industry possesses a complex industrial structure in which multi-stage and intensive chemical reactions occur, including raw material preparation, sintering, coke production, blast furnace processes, steelmaking, and rolling operations. Various chemical substances used during these processes or generated as by-products create significant occupational risks to which workers may be exposed. Toxic gases such as carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NOx), and hydrogen sulfide (H_2S), along with metal oxide fumes, heavy metal particles, acid-base solutions, lubricating and cooling chemicals, and volatile organic compounds (VOCs), constitute the primary chemical hazards in the sector. Exposure to these substances through inhalation, skin contact, or ingestion may lead to acute poisoning, respiratory irritation, dermatitis, eye irritation, central nervous system effects, and, in the long term, serious health outcomes such as occupational asthma, chronic obstructive pulmonary disease (COPD), and certain types of cancer. Therefore, the accurate identification of chemical risk factors, the implementation of process-based hazard analyses, regular workplace environmental measurements, and the effective application of engineering controls are of critical importance. Additionally, the proper selection of personal protective equipment, continuous training programs for employees, and chemical management systems compliant with international standards constitute the fundamental components of creating a safe working environment within the sector. This study aims to provide a comprehensive assessment of chemical risk factors encountered in the iron and steel industry by presenting an integrated framework on exposure sources, health effects, and control strategies.

Keywords: Iron and steel, toxic gases, chemical risk factors, health

1.Introduction

The iron and steel sector are considered one of the cornerstones of economic, technological, and infrastructural development in today's industrialized societies. A wide range of industries, including construction, automotive, energy, machinery manufacturing, defense, transportation, and infrastructure projects, meet a significant portion of their needs for durable and high-performance materials through iron and steel production [1]. Therefore, the sector is of critical importance not only in terms of production volume but also in terms of its strategic position in the global supply chain. However, the fact that these large-scale production activities rely on intensive chemical processes causes various risks for sector employees, the environment, and industrial environmental health. The most prominent of these risks are the chemical risk factors that can arise at every stage of production [2]. Steel production is a complex process involving numerous thermal and chemical reactions, starting from the ore preparation stage and continuing through sintering, pelletizing, coke production, blast furnace processes, steel production (BOF and EAF), secondary metallurgical processes, continuous

casting, and rolling. Each of these processes inherently involves the use of chemical substances, chemical reactions, and the formation of byproducts [3]. For example, carbon monoxide (CO), nitrogen oxides (NOx), sulfur oxides (SOx), and various organic toxic compounds; polycyclic aromatic hydrocarbons (PAH), volatile organic compounds such as benzene and toluene arising from coke production; hydrogen sulfide (H_2S), carbon dioxide (CO_2), and metal oxide dusts formed in blast furnace processes; heavy metal-containing fumes, dioxins, and furans arising in electric arc furnaces (EAF); toxic flux fumes and refractory material dusts released in secondary metallurgy are among the most well-known examples of these risks [4]. It is known that chemical risk factors arise not only during the production phase, but also in auxiliary operations such as storage, transportation, sampling, maintenance, waste management, and energy production [5]. Therefore, chemical risk management has become a multidimensional field across the industry that requires high technical knowledge and a systematic approach in terms of both occupational hygiene and process safety. Particularly heavy metal dusts (lead, cadmium, chromium, nickel), ultrafine particles (PM1, PM2.5), acid vapors (HCl, HF), combustion gases, oxidizing agents, chemical mixtures that can create explosive atmospheres, and hazardous substances that can react at high temperatures pose a serious threat to industry workers [6].

One of the main reasons why chemical risk factors are such a significant problem in the iron and steel industry is that most production processes take place under high temperature and high pressure [7]. These conditions accelerate the instantaneous reactions of chemical substances, increase their volatility, and facilitate their dispersion into the working environment. Thermal decomposition products caused by high temperatures, combustion gases, and metal fumes often contain particles that are invisible to the naked eye but are respirable. These particles can enter the body through the respiratory tract of workers, causing acute and chronic occupational diseases. Particularly with long-term exposure, health problems such as COPD, pneumoconiosis, carcinogenic effects, nervous system damage, hematological disorders, skin irritations, and eye damage may occur [8]. Similarly, leaks, spills, and vaporization events that may occur during the dilution, mixing, or feeding of chemicals used in production facilities are other factors that make it difficult to control chemical risks [9]. Lubricants, hydraulic fluids, refractory coating chemicals, pH regulators, surface cleaners, corrosion inhibitors, and various auxiliary chemicals used in the iron and steel industry also pose risks in terms of occupational hygiene. Some of these substances are flammable, irritating, or toxic and can endanger worker safety if proper ventilation, personal protective equipment (PPE), and process control systems are not used [10].

Chemical risk factors directly affect not only worker health but also environmental health and facility safety. Improperly stored or disposed of chemicals can contaminate soil, groundwater, and surface water [11]. The ignition of chemical substances due to high temperatures can increase the risk of fire and explosion. Furthermore, when flue gas treatment systems are inadequate, chemical compounds released into the atmosphere negatively impact regional air quality and lead to violations of national and international emission standards. Therefore, the proper management of chemical risks is not only an occupational health and safety requirement but also indispensable in terms of legal compliance, sustainability, and corporate responsibility [12]. In recent years, with the widespread adoption of international standards (ISO 14001, ISO 45001, REACH, OSHA, etc.), new technical applications for assessing, monitoring, and controlling chemical risks in the iron and steel industry have gained importance [13]. Emissions measurement systems, chemical exposure monitoring devices, process control automation, artificial intelligence- supported risk prediction systems, and advanced ventilation technologies used in modern iron and steel plants make chemical risk management more effective. However, since it is not possible to completely eliminate risks, human-centered practices such as occupational hygiene measurements, continuous training, safety procedures, improvement of PPE use, and emergency management remain important [14]. In this context, a comprehensive examination of chemical risk factors in the iron and steel industry is critical, both in terms of worker health and safety and the sustainability of production processes [15]. The purpose of this article is to scientifically evaluate the chemical risks arising in all stages of iron and steel production, explain the mechanisms of these risks, analyze exposure levels, and present effective control methods within an academic framework. Furthermore, challenges encountered in chemical risk management and areas requiring improvement will be addressed in light of current industry practices, international standards, and recent research. Thus, the aim is to contribute to the academic literature and provide an assessment that serves as a guide for practitioners [16].

1. Chemical Hazard Sources in Iron and Steel Production Processes

1.1. Raw Material Preparation and Ore Enrichment

The initial stages of the iron and steel production chain, including raw material preparation**,** crushing and grinding**,** classification**,** magnetic separation**,** flotation**,** sintering, and pellet preparation, involve numerous chemical hazards due to mineralogical transformations, chemical reactions, and dust and gas emissions [17]. The chemical risk factors that arise at this stage directly affect both worker health and process safety.

The chemical hazard sources encountered on an industrial scale, classified by process and consistent with the literature, are detailed below:

1.1.1 Dust generated during the iron ore crushing and grinding stage [18]

- ✓ Iron oxide dusts containing hematite, magnetite, limonite, and siderite
- ✓ Free silica (SiO_2) in fine fractions
- ✓ Alumina (Al_2O_3) and clay minerals associated with impurities in the ore
- ✓ Trace elements of toxic metals found in blast furnace and sinter raw materials

Health risks: Silicosis, chronic obstructive pulmonary disease (COPD), metal fume fever, heavy metal toxicity.

1.1.2 Chemical Risks in Raw Material Storage and Transfer Stages

Oxidation and heating reactions [19]**:**

- ✓ Self-heating in fine ore piles,
- ✓ Oxidative heat release in ores containing copper and magnetite,
- ✓ High temperatures causing CO, CO_2, and VOC emissions.

Moisture and ore interactions [20]**:**

As a result of contact with moisture in ore piles:

- ✓ Acid mine drainage
- ✓ H_2S gas formation as a result of reaction with sulfide minerals

1.2. Sintering Plant

Sintering is a thermochemical process based on the agglomeration of fine-grained ore, coke dust, and various additives at temperatures ranging from 1200 to 1300 °C to produce sinter in the form of pieces suitable for use in blast furnaces [21,22]. This process is a production stage that generates numerous chemical hazards due to high heat and oxidation-reduction reactions. Gas and emission values obtained from an example iron and steel plant production process are shared and interpreted below.

Table 1. Average Concentrations in Sintering Gases

Pollutant	Average Concentration	Typical Range	Legal Limit (EU BAT)*	Description
Dust (PM)	25 mg/Nm³	18–35 mg/Nm³	10–20 mg/Nm³	After bag filter
NOx	320 mg/Nm³	270–360 mg/Nm³	180–350 mg/Nm³	Thermal + Fuel NOx
SOz	180 mg/Nm³	120–240 mg/Nm³	50–200 mg/Nm³	Coke sulfur effect
CO	950 mg/Nm³	700–1200 mg/Nm³	No limit (critical for occupational health)	Unburned areas
COz	16 vol.%	15–18%	–	Carbon cycle associated with the blast furnace
Oz	6.2 vol.%	5.5–6.8%	–	Draft control result
VOC	4 mg/Nm³	2–6 mg/Nm³	2–20 mg/Nm³	Organic pollutants
PAH	0.08 mg/Nm³	0.05–0.12 mg/Nm³	–	Including benzo(a)pyrene
HCl	6 mg/Nm³	3–9 mg/Nm³	1–10 mg/Nm³	PVC-containing recovery dusts
HF	1.2 mg/Nm³	0.6–1.5 mg/Nm³	0.5–2 mg/Nm³	Fluorinated minerals
Dioxin/Furan (PCDD/F)	0.20 ng/Nm³ (I- TEQ)	0.15–0.35	0.04–0.20	Most critical toxic compound

*BAT: Best Available Techniques (EU Environmental Legislation)

The sinter gas emission values given in Table 1 show that the sintering process in a typical

integrated iron and steel plant carries multidimensional risks in terms of both the environment and occupational health. Most emissions are close to the EU BAT (Best Available Techniques) reference limits; however, critical threshold values are reached for some pollutants (especially dust, CO, and dioxin/furan). This indicates that process control is generally stable but optimization is needed for certain emission types.

PM, in particular, is the characteristic and most prominent pollutant of sintering and can remain above BAT limits despite the use of bag filters. High CO values indicate that complete combustion cannot be achieved in some areas of the bed, posing a serious exposure risk, not only environmentally but especially in terms of occupational health. SO_2 **and** NOx levels are mostly compliant with regulations but are sensitive to the sulfur content of the coke used and combustion conditions. Although organic pollutants such as VOC **and** PAH are low, the carcinogenic types within PAH require continuous monitoring. HCl **and** HF indicate that the raw material composition is heterogeneous and that chlorine and fluorine contained in recovered dusts, in particular, affect the process. PCDD/F levels, which are close to the BAT upper limit, confirm once again that the sintering process is a high-risk point for dioxin formation.

Overall, the table shows that although the sintering process is controlled by modern gas treatment systems, it requires process optimization and raw material management for critical pollutants; it also shows that the data obtained must be considered in conjunction with occupational health risk assessment. In this context, fuel quality, air distribution, heat profile, and the performance of treatment equipment stand out as the most sensitive control parameters for reducing emissions.

Table 2. Heavy Metal Emissions from Sintering

Heavy Metal	Emission	Typical Industry	Source
Pb (Lead)	0.65	0.4–1.2	Ore and recycled powder
Zn (Zinc)	1.8	1–3	Scrap dust and recycling
As (Arsenic)	0.04	0.02–0.06	Trace elements in iron ore
Cd (Cadmium)	0.01	0.005–0.02	Ore impurity
Hg (Mercury)	0.003	0.002–0.006	Minerals containing organic
Total Cr	0.15	0.10–0.25	Ore and refractory wear
Ni (Nickel)	0.2	0.12–0.28	Ore content

The data presented in Table 2 allows for a comparative assessment of heavy metal emissions from the sintering process, both in absolute values and in terms of typical industry ranges. The measurements obtained show that most heavy metal components, particularly Pb, Zn, and Ni, fall within the typical ranges reported in the industry literature. Specifically, the Zn (1.8 mg/Nm^3) and Pb (0.65 mg/Nm^3) values are consistent with the average levels observed in facilities where recycled dust is incorporated into the process flow. However, the fact that elements with high toxicity coefficients, such as As, Cd, and Hg, were measured at low concentrations can be considered an indicator of the quality of the raw materials used and the effectiveness of the gas purification system.

It is understood that emissions from elements such as Cr and Ni vary depending on ore content and refractory wear. The table provides a comprehensive overview of the heavy metal emission profile of the sintering process, revealing that parameters such as the mineralogical structure of

the raw material, the recycling rate, and the condition of the process equipment are decisive factors in emission levels. In this context, the data emphasizes the importance of process-controlled improvement efforts, particularly interventions aimed at increasing metal recovery and treatment efficiency.

Table 3. Sinter Plant Emission Sources and Percentage Distribution

Process Step	**Dust (%)**	**NO_x (%)**	**SO_2 (%)**	**CO (%)**	**Description**
Raw material preparation (crushing-screening)	22	–	–	–	Powder main source
Mixer-blender line	8	–	–	–	If humidity is low, dust increases
Sintering machine (combustion zone)	55	82	88	91	Primary chemical emission source
Cooling area	10	8	7	5	Gas discharge from hot material
Recycling & crushers	5	5	5	3	Mechanical abrasion dusts

When examining the types and proportional distribution of emission sources associated with the sintering process in Table 3, it is seen that the sintering machine has a dominant position, particularly in chemical gas emissions. The sintering machine accounts for 82% of total NOx emissions, 88% of SO_2, and 91% of CO, demonstrating that it is the main pollutant source in the process. This situation shows that the sintering bed area, where high-temperature combustion and reduction reactions occur intensively, plays a critical role in the formation of chemical emissions. In terms of dust emissions, the distribution is more widespread, with raw material preparation (22%) and the main sintering area (55%) accounting for the majority of the total dust load. This result indicates that both mechanical crushing and screening processes and the physical-chemical reactions occurring on the sintering bed contribute to dust formation. Furthermore, the 8% dust emission observed in the mixer, mixer- line supports the notion that moisture control is a decisive parameter in dust formation.

The contribution of the cooling zone to emissions is relatively low, with limited increases (in the range of 5–8%) observed, particularly for NOx and SO_2, due to gases released from hot material. In the recycling and crusher lines, low rates for all pollutants (in the range of 3–5%) are noteworthy, indicating a more limited emission load due to mechanical abrasion.

Overall, the table shows that the critical point where chemical gas emissions are concentrated in the sintering process is the sintering machine, while both mechanical and thermochemical processes play a decisive role in dust emissions. This distribution contributes to the clear definition of the points that need to be focused on in process control and emission reduction strategies.

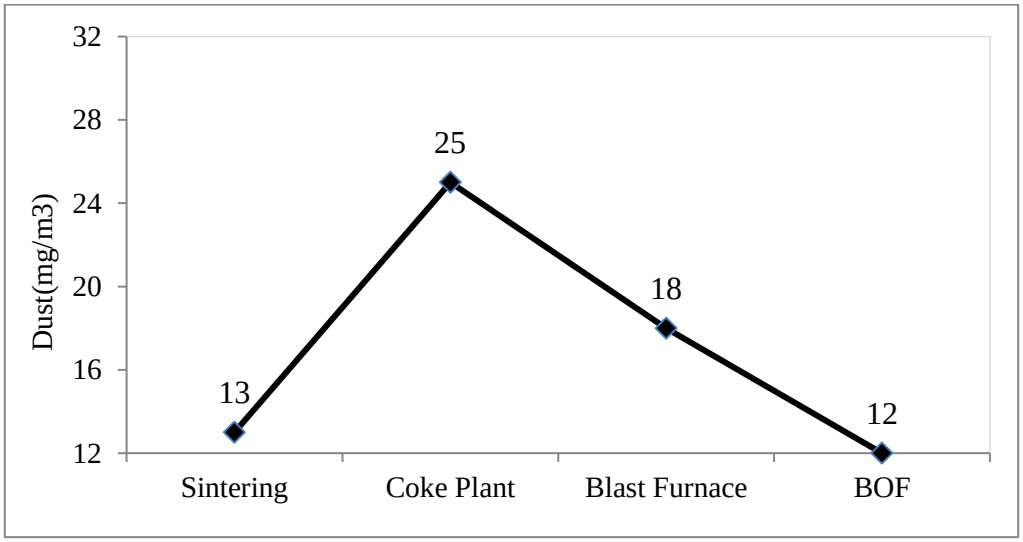

Figure 1. Dust emission values in iron and steel plants

Figure 1 shows a comparative view of dust concentrations measured in different processes in iron and steel production. The highest dust emissions were recorded in the Electric Arc Furnace (EAF) and Coke Oven processes, indicating that these units are more risky operations in terms of particle formation. The BOF process has the lowest dust values, indicating the effectiveness of the applied purification systems. Sintering and secondary metallurgy stages produce medium-level emissions. Overall, the graph reveals a clear difference in emissions between processes and that some stages require more intensive control. CO emission values in iron and steel plants are given in Figure 2.

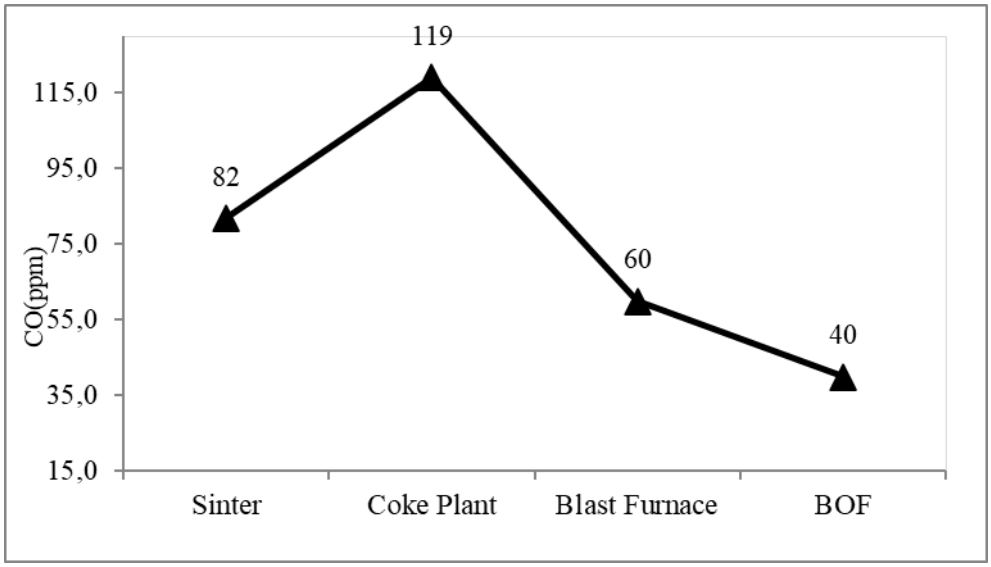

Figure 3. CO emission values in iron and steel plants.

CO (carbon monoxide) emissions in iron and steel plants are a critical pollutant parameter, particularly in coke batteries, sintering plants, and blast furnace processes, due to combustion inefficiency, incomplete oxidation, and raw gas leaks. CO concentrations are sensitive to process conditions and are typically measured in the hundreds to thousands of ppm range in combustion chambers and blast furnace outlet gases. Controlling emissions requires ensuring complete combustion**,** optimizing the combustion air and fuel ratio**,** improving closed-loop gas

collection systems**, and** effectively utilizing continuous emission monitoring systems (CEMS). Sudden increases in CO levels are often indicative of combustion instability**,** fuel-air imbalance**, or** gas leaks, making it a critical early warning parameter for process safety and worker health.

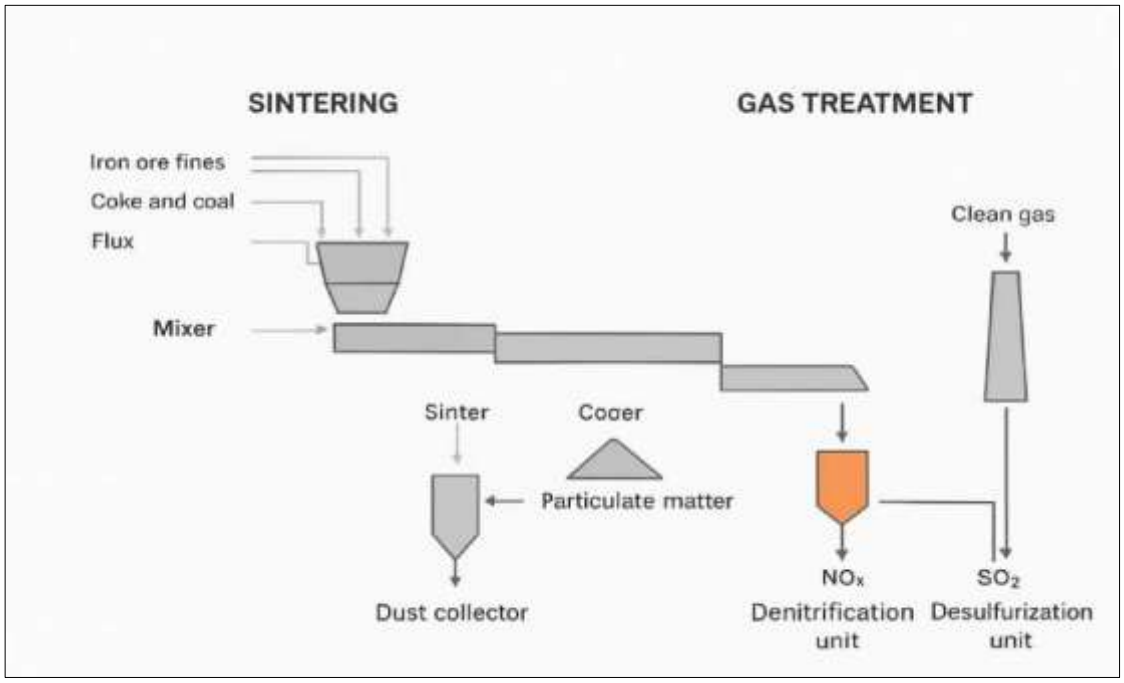

Figure 3. Sintering and gas purification system process flow diagram [23].

The sintering and gas purification system process flow diagram is shown in Figure 3. Chemical hazards in raw material preparation and ore enrichment processes, which constitute the first stage of the iron and steel industry, occur in a wide range, such as dust and metal particles, VOCs, heavy metals, corrosive liquids, flotation reagents, sinter and pellet gas emissions, fuel oil combustion products, acidic drainage gases, and CO, NOx and SOx emissions generated during the process.

If these hazards are not controlled, they can lead to serious occupational diseases, environmental pollution, and process safety problems among workers.

1.3. Coke Production

During high-temperature coal pyrolysis in coke batteries, numerous volatile chemicals are released. The main chemical hazards in metallurgical coke production are concentrated in this stage. Coal pyrolysis occurs at temperatures of 1000–1200 °C inside the furnace [24]. The gases formed during pyrolysis that are critical to occupational health are shown in Table 4.

Table 4. Gases formed during pyrolysis that are critical for occupational health

Gas	Source of Formation	Health Risk
CO (Carbon monoxide)	Thermal decomposition of coal	Toxic, suffocating
H_2S (Hydrogen sulfide)	Decomposition of sulfur compounds	Neurotoxicity, risk of lethal dose
HCN (Hydrogen cyanide)	Nitrogen compounds	Acute toxicity, rapid effect
NHs (Ammonia)	Decomposition of nitrogenous organic structures	Corrosive, respiratory irritant
SO2 / SOx	Sulfur content	Respiratory irritant
NOx	High-temperature reactions	Risk of pulmonary edema
Benzene, Toluene, Xylene (BTX)	Volatile aromatic hydrocarbons	Carcinogenic / hematotoxic
PAHs (Benzo[a]pyrene, etc.)	Pyrolysis of organic structures	High carcinogenic effect
VOCs	Coke oven gas components	Explosive/toxic

In metallurgical coke production, when coal undergoes pyrolysis in an oxygen-free environment at temperatures between 1000-1200 °C, the thermal decomposition of the coal's organic matrix releases a multi-component gas mixture. This gas phase presents a complex structure containing combustible components with high calorific value, such as hydrogen (H2), methane (CH4), and carbon monoxide (CO), as well as toxic and corrosive components, such as hydrogen sulfide (H2S), ammonia (NH3), and hydrochloric acid (HCl). In addition, organic volatiles such as benzene, toluene, xylene (BTX), and polyaromatic hydrocarbons (PAH) are also formed intensively during this process.

The quantity and character of the gas composition are closely related to the petrographic properties of the coal, the volatile matter content, the furnace temperature profile, and the carbonization time. This gas mixture is both an important energy source in terms of process efficiency and carries critical risk factors in terms of occupational health, environmental management, and the performance of gas treatment systems. Therefore, accurately monitoring the formation mechanism and component distribution of pyrolysis gases is essential for optimizing the coking process and controlling environmental emissions. The coke oven and gas treatment flowchart is shown in Figure 4.

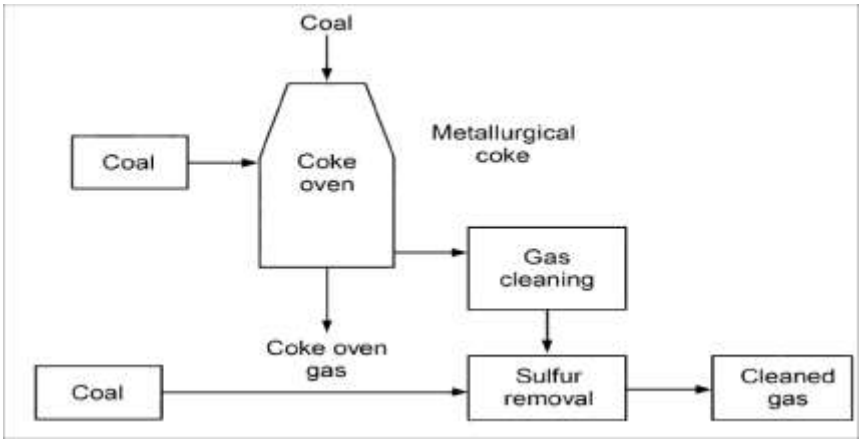

Figure 4. Coke oven and gas treatment flowchart [25].

The Coke Oven and Gas Treatment Flowchart shows the basic stages of the metallurgical coke production process and the operation of the by-product gas treatment line from a holistic perspective. The diagram covers the process starting with the feeding of coal into the coke oven, resulting in high-temperature pyrolysis, the production of metallurgical coke as a solid product, and the formation of coke oven gas. The flowchart further highlights that the resulting coke oven gas undergoes sequential treatment processes gas cleaning, desulfurization, and final gas purification—to make it suitable for industrial use. The diagram clearly illustrates the interdependence between coke production and gas purification processes and reflects the importance of process integration in terms of environmental performance and occupational safety through an analytical approach.

2. Conclusions and Recommendations

The iron and steel industry is a sector with a high level of chemical risk due to its multi-stage process structure and production line based on intensive chemical reactions. This study addresses the chemical hazards arising in the sector from a holistic perspective, systematically examining the effects of toxic gases, metal oxide fumes, volatile organic compounds, heavy metal particles, and other process-related harmful agents on worker health. The findings show that chemical exposures are not only a natural consequence of the process; deficiencies in measurement, monitoring, engineering controls, and managerial practices also increase risk levels.

The iron and steel industry is one of the sectors with the highest risk class in terms of chemical risk factors. Exposure to toxic gases, metal vapors, carcinogens, and solvents can lead to acute and chronic health effects. These risks can be significantly reduced through effective engineering controls, regular monitoring, appropriate PPE use, and process improvements. Compliance with international standards and a continuous improvement approach are critical for both protecting worker health and ensuring sustainable production.

In order to establish a sustainable occupational health and safety approach in the sector, it is essential to accurately identify chemical risk factors, perform process-based hazard analyses, and implement control strategies that comply with international standards. In this context, the widespread use of closed system designs, the use of effective ventilation and purification technologies, regular environmental measurements, and increased use of reliable personal protective equipment play a critical role in reducing exposure. In addition, continuous training of employees, keeping chemical management plans up to date, and evaluating all processes within the scope of an integrated risk management system will contribute significantly to the development of a safety culture across the sector.

In conclusion, controlling chemical risks in the iron and steel industry requires a multi-layered approach that goes beyond technical measures alone, supported by corporate governance, employee participation, regular monitoring, and science-based decision-making mechanisms. Efforts undertaken within this framework will enable both the protection of worker health and the transformation of production processes into more sustainable, efficient, and safe operations.

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Mo-Sm_2O_3 KOMPOZİTLERİNİN MİKRO YAPISI, YOĞUNLUĞU VE SERTLİK GELİŞİMİ

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ÖZET

Molibden (Mo) ve onun alaşımları, yüksek sıcaklıklı uygulamalarda tercih edilen malzemelerdir çünkü yüksek erime sıcaklığı, düşük ısıl genleşme oranı, termal şoklara karşı üstün direnç ve ısıl yorgunluğa karşı olağanüstü bir dayanıklılık gibi niteliklere sahiptirler. Fakat, saf molibdenin yüksek sıcaklıklardaki yeniden kristalleşme sıcaklıkları, dayanıklılık ve aşınma direncinde artan ihtiyaçları karşılamada çeşitli kısıtlamalarla karşılaşabilir. Bu sebeple, saf molibdenin yüksek ısıda aşınmaya karşı daha iyi bir direnç göstermesi için, Mo matrisli kompozitler tasarlanmıştır. Mo matrisli kompozitler, genelde yüksek sıcaklık koşullarında faaliyet gösteren uygulamalarda kullanılan yapısal bileşenler için daha dayanıklı ve etkili bir seçenek sunmaktadır. Bu çalışma molibden (Mo) içerisine farklı oranlarda (hacimce % 3, 6 ve 9) samaryum oksit (Sm_2O_3) ilave edilerek toz metalürjisiyle üretilen kompozitlerin mikroyapısal gelişiminin incelenmesi ve sertliğinin arttırılması amaçlamaktadır. Buna ilaveten üretilen kompozitin yoğunluk ve sertlik özellikleri de incelenmiştir. Mikroyapı incelemeleri için SEM-EDS analizi kullanılırken, yoğunluk için Arşiment prensibi ve sertlik için Vikers sertlik testi kullanılmıştır. Mikroyapı sonuçları (hem SEM hem de MAP) Sm_2O_3 partiküllerinin Mo matrisinde nispeten homojen dağıldığını göstermiştir. XRD sonuçları Mo ile Sm_2O_3 arasında herhangi bir fazın oluşmadığını göstermiştir. Deneysel yoğunluklarda ve bağıl yoğunluklarda düşüşler meydana gelmiştir. %9 Sm_2O_3 ilavesinde deneysel yoğunluk 8.8 g/cm^3 iken bağıl yoğunluk % 88.2 olarak ölçülmüştür. Mekanik özellik olarak değerlendirilen sertlik sonuçlarına göre sertliklerde belirgin artış olmuştur. En yüksek sertlik %9 Sm_2O_3 ilavesinde 318.2 HV0.5 olarak ölçülmüştür. Bu değer katkısız Mo matrisine göre sertliğin yaklaşık %77.5 oranında arttığını göstermiştir.

Anahtar kelimeler: Mo, Sm_2O_3, kompozit, mikroyapı, sertlik

MICROSTRUCTURE, DENSITY AND HARDNESS EVOLUTION OF Mo-Sm_2O_3 COMPOSITES

ABSTRACT

Molybdenum (Mo) and its alloys are preferred materials in high-temperature applications because they possess qualities such as high melting point, low thermal expansion rate, superior resistance to thermal shock, and exceptional resistance to thermal fatigue. However, the recrystallization temperatures of pure molybdenum at high temperatures can present various limitations in meeting the increasing demands for durability and wear resistance. For this reason, Mo-matrix composites have been designed to provide pure molybdenum with better resistance to wear at high temperatures. Mo matrix composites offer a more durable and effective option for structural components used in applications operating under high-temperature conditions. This study aims to investigate the microstructural development and increase the hardness of composites produced by powder metallurgy by adding samarium oxide (Sm_2O_3) at different ratios (3%, 6%, and 9% by volume) to molybdenum (Mo). In addition, the density and hardness properties of the produced composite were also investigated. SEM-EDS analysis was used for microstructure investigations, while the Archimedes principle was used for density and the Vikers hardness test was used for hardness. Microstructure results (both SEM and MAP) showed that Sm_2O_3 particles were relatively homogeneously distributed in the Mo matrix. XRD results showed that no phase formed between Mo and Sm_2O_3. Decreases occurred in experimental densities and relative densities. At 9% Sm_2O_3 addition, the experimental density was 8.8 g/cm^3, while the relative density was measured as 88.2%. According to the hardness results, which were evaluated as a mechanical property, there was a significant increase in hardness. The highest hardness was measured as 318.2 $HV_{0.5}$ with a 9% addition of Sm_2O_3. This value indicates that the hardness increased by approximately 77.5% compared to the Mo matrix without any additions.

Keywords: Mo, Sm_2O_3, composite, microstructure, hardness

1. GİRİŞ

Dünya genelinde enerji kullanımı sürekli bir yükseliş göstermektedir. İnsanlığın hayatta kalabilmesi için enerji tüketimini aşağı çekmesi gerekmektedir. Bu hedefe ulaşmanın en belirgin yolu, makinelerin ısıya maruz kalan bölgelerindeki malzemelerin işleme sıcaklığını yükselterek enerji üreten makinelerin termal verimliliğini yükseltmektir [1]. Molibden (Mo) ve alaşımları, yüksek erime noktası, düşük termal genleşme, termal şoka karşı mükemmel direnç ve termal yorgunluğa karşı olağanüstü dayanıklılıkları nedeniyle yüksek sıcaklık uygulamaları için tercih edilen malzemelerdir [2,3]. Mo ve alaşımları son yıllarda itina ile geliştirilmektedir. Bu konu hakkında elde edilen bulgular pek çok yayında yer almıştır, bunlardan bazılarını örnek olarak gösterebiliriz [4–6]. Elbette, bu tür yüksek sıcaklığa dayanıklı bileşimlerin en büyük sorunu, metal alaşımlarında sıkça karşılaşılan dayanıklılık (sünme direnci) ile kırılma dayanıklılığı arasındaki çelişkidir [7,8]. Bu yüzden, saf molibdenin yüksek sıcaklıklarda aşınmaya karşı daha iyi direnç göstermesi amacıyla Mo matris kompozitleri tasarlanmıştır. Mo matris kompozitleri, genelde yüksek sıcaklık uygulamalarında kullanılan yapısal elemanlar için daha sağlam ve etkili bir seçenek sunar. Cheng vd. [9]'nin yaptığı çalışmada La_2O_3 ilaveli Mo–La_2O_3 kompozitleri (0, 0,5, 1,0, 1,5 ve 2,0 ağırlıkça %) ince tane yapıları ve artan yeniden kristalleşme sıcaklıkları sergilemiştir. Kompozitler, %0,5–1,0 ağırlıkça La_2O_3'te önemli ölçüde artırılmış mukavemet (saf Mo'dan 100 MPa daha fazla) ve uzama (saf Mo'nun iki katı) gösterir, ancak uzama %1,5 ağırlıkça'nın üzerinde azalır. Güçlendirme, tane içi ve tane sınırı mekanizmaları yoluyla gerçekleşir ve sünek kırılma, tane arası parçacıklarda mikro çatlak çekirdeklenmesinden etkilenir. Testler, %1,0–1,5 ağırlıkça La_2O_3'te optimum mukavemet ve uzama özellikleri olduğunu gösterir; yüksek sıcaklıkta deformasyon, tane arası ve tane içi hasarın etkisiyle mikro boşluk birleşmesi ve mikro çatlak yayılımını içerir. Jing vd. [10], oda sıcaklığı ile yüksek sıcaklıklarda üstün mekanik özelliklere sahip nano yapılı Mo-ZrC alaşımını, nano boyutlu ZrC dağılımı ve arayüz kontrolü ile geliştirmişlerdir. Mo-ZrC alaşımının üstün mekanik özellikleri ve ısıya dayanıklılığı, nano boyutlu ZrC parçacıklarının dağılım güçlendirilmesi, ince taneli güçlendirme ve tane sınırlarının temizlenmesi gibi etkilerinin bir araya gelmesinden kaynaklandığı bildirilmiştir. Bu araştırma, molibden (Mo) içine çeşitli oranlarda (hacimce % 3, 6 ve 9) samaryum oksit (Sm_2O_3) eklenerek toz metalürjisi ile elde edilen kompozitlerin mikroyapısının incelenmesi ve sertlik seviyesinin yükseltilmesi hedeflenmektedir. Ayrıca, üretilen kompozitin yoğunluk ve sertlik özellikleri de değerlendirilmektedir.

2. DENEYSEL ÇALIŞMALAR

Mo matrisli, Sm_2O_3 takviyeli kompozit malzemelerin toz metalürjisi ile üretilmiştir. Üretimde kullanılan tozlar Mo, %99.95 saflıkta ve 10 µm tane boyutuna sahip; Sm_2O_3 ise %95 saflıkta ve -325 mesh tane boyutuna sahiptir. Kompozitlerin üretiminde kullanılan toz bileşim oranları Tablo 1'de verilmiştir.

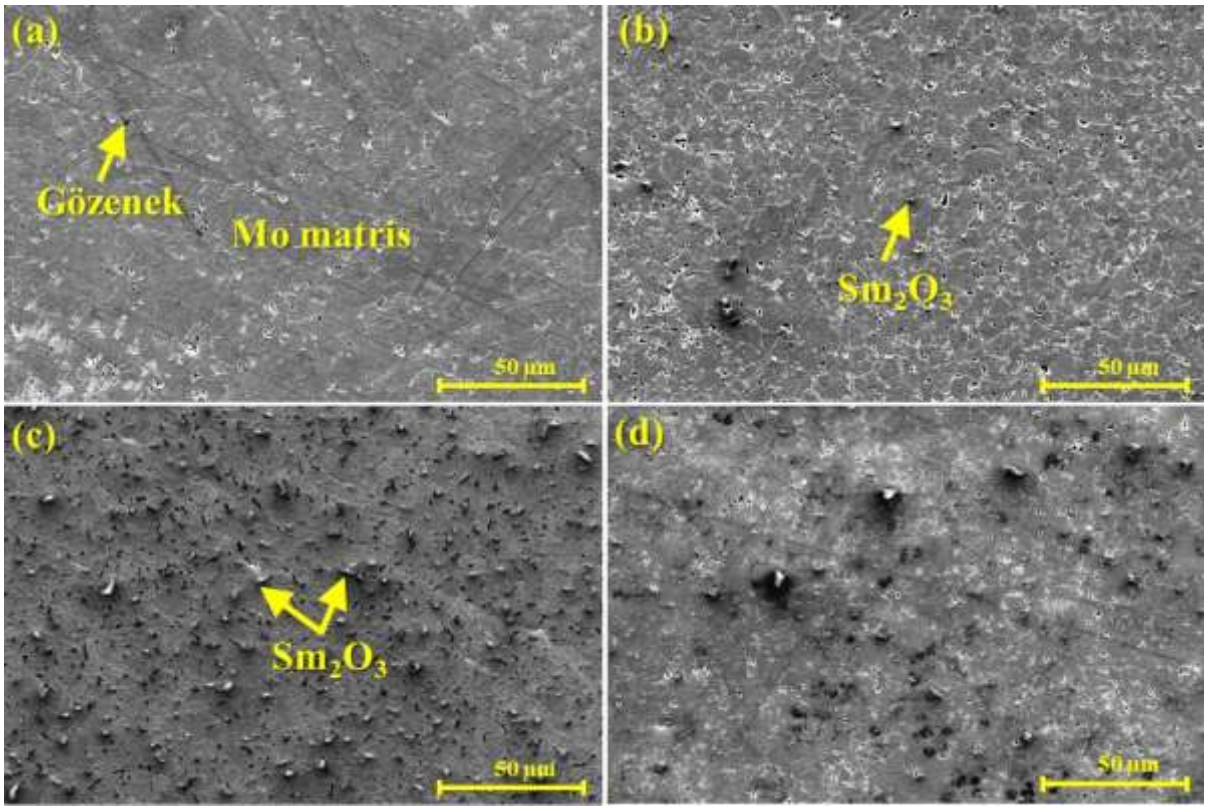
Tablo 1: Toz bileşim oranları

Numune grubu	Bileşim (% hacim)	
	Mo	Sm_2O_3
1	100	-
2	97	3
3	94	6
4	91	9

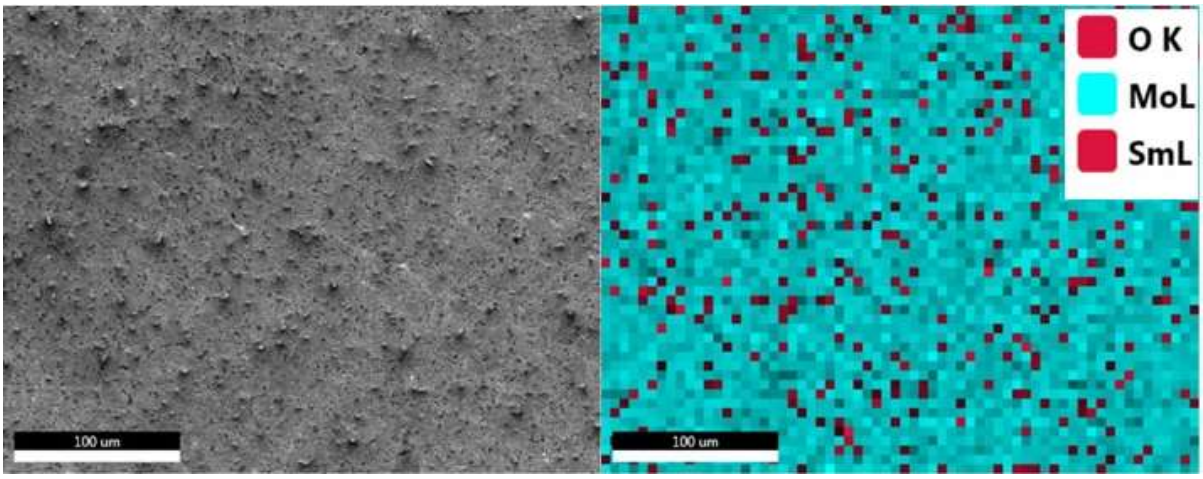
Öncelikle, tozlar Tablo 1'de belirtilen oranlarda 1 saat boyunca bir toz karıştırma mikserinde (turbula) karıştırılmıştır. Ardından, bu toz karışımı, SPECAC GS15011 marka ve model bir hidrolik pres ile 20 mm çapında ve 5 mm kalınlığında pelletler haline getirilmiştir. Bu işlem sonucunda elde edilen pelletler, PROTHERM PTF 18/50/300 marka ve model yüksek sıcaklıkta çalışan bir tüp fırında argon gazı ortamında 1750 °C'de 1 saat süreyle sinterlenmiştir. Metalografik numune hazırlığı tamamlandıktan sonra, numuneler mikroyapı analizi için Murakami çözeltisi kullanılarak dağlanmıştır. Numunelerin faz yapısı ve mikroyapı analizi bir taramalı elektron mikroskobu ve bir X-ışını difraktometresi aracılığıyla da incelenmiştir. Numunelerin deneysel yoğunlukları, Arşimet ilkesine ve ASTM B962-08 standardına dayanarak belirlenmiştir. Bağıl yoğunluklar, deneysel yoğunlukların teorik yoğunluklara bölünmesi ile hesaplanmıştır. Numunelerin sertlik değerleri, mikrosertlik cihazı kullanılarak 500 gramlık bir yük altında 15 saniyelik bir bekleme süresiyle ölçülmüştür.

3. SONUÇLAR ve TARTIŞMA

Üretilen kompozitlerin SEM görüntüleri Şekil 1'de verilmiştir. Mo matrisi içerisinde Sm_2O_3 partikülleri homojen olarak dağılmıştır. Bu durum ayrıca Şekil 2'deki MAP analizi ile de desteklenmektedir. Partiküllerin homojen dağılımı hem mekaniksel hemde fiziksel özelliklere olumlu etki etmektedir. SEM incelemelerinde ayrıca çok azda olsa gözenek oluşumu görülmektedir.

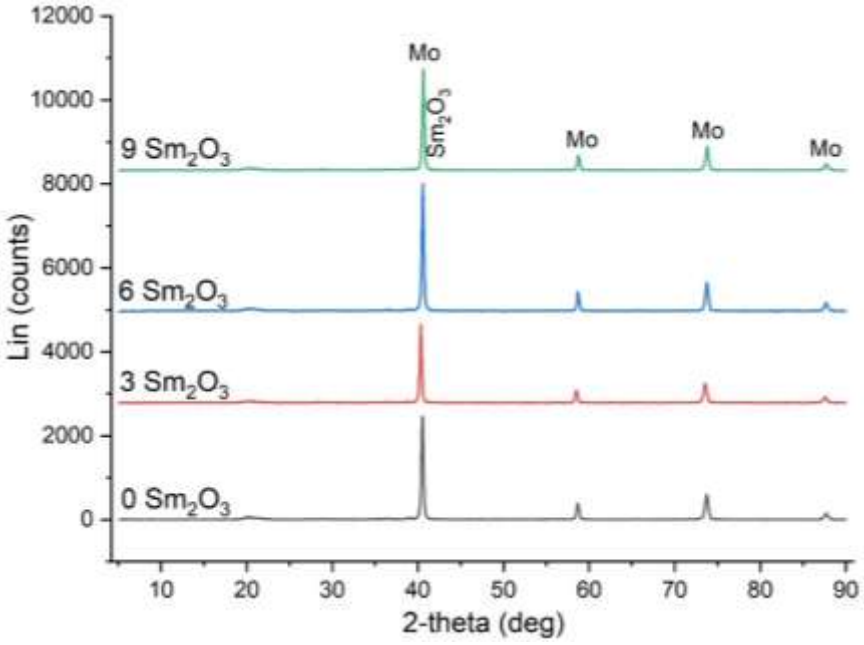


Şekil 1: SEM görüntüleri: (a) 0 Sm_2O_3, (b) 3 Sm_2O_3, (c) 6 Sm_2O_3 ve (d) 9 Sm_2O_3



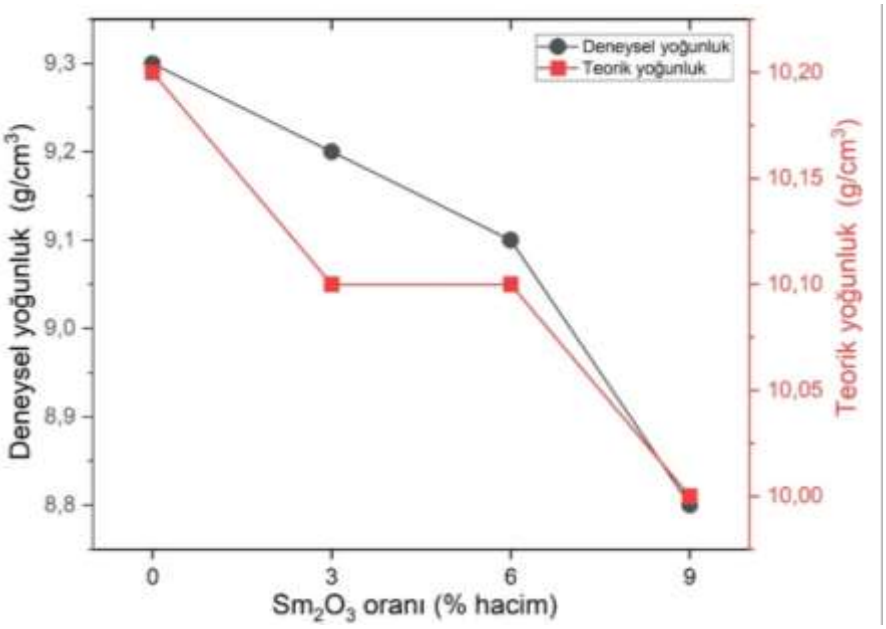
Şekil 2: Mo-6 Sm_2O_3 kompozitin MAP analizi

Şekil 3'de XRD analizi grafiği verilmiştir. Mikroyapıda kompoziti oluşturan Mo ve Sm_2O_3 haricinde herhangi bir faz oluşmamıştır. Üretim esnasında numunelerde herhangi bir oksit oluşmadığı da XRD grafiğinden anlaşılmaktadır.



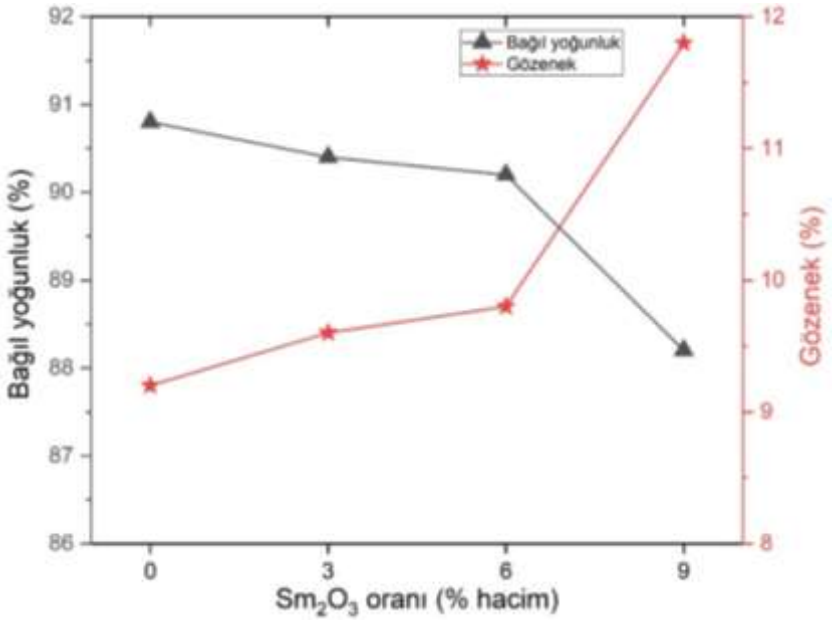
Şekil 3: Mo-Sm_2O_3 kompozitlerin XRD analizi

Mo matrisine ilave edilen Sm_2O_3 partiküllerin deneysel yoğunluk üzerine etkisi Şekil 4'de verilmiştir. % 0, 3, 6 ve 9 Sm_2O_3 katkısına bağlı olarak sırasıyla deneysel yoğunluklar 9.3, 9.2, 9.1 ve 8.8 g/cm^3 olarak ölçülmüştür. Bu durum Sm_2O_3'ün yoğunluğunun (8.35 g/cm^3) Mo'ya göre (10.2 g/cm^3) düşük olmasından kaynaklanmaktadır.



Şekil 4: Mo-Sm_2O_3 kompozitlerin deneysel ve teorik yoğunlukları

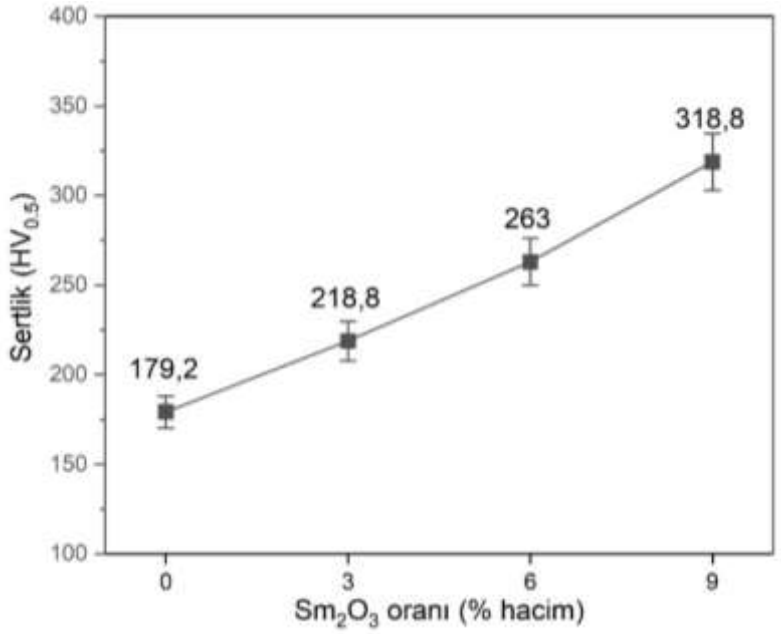
Deneysel yoğunlukların teorik yoğunluklara bölünmesiyle bağıl yoğunluklar hesaplanmıştır. Bağıl yoğunluklardan yola çıkarak kompozitlerin gözenekleri bulunmuştur. Şekil 5'de kompozitlerin bağıl yoğunlukları ve gözenek miktarı verilmiştir. Sm_2O_3 ilavesiyle bağıl yoğunluklarda azalma olurken, gözenek miktarında artış meydana gelmiştir.



Şekil 5: Mo-Sm_2O_3 kompozitlerin bağıl yoğunluklar ve gözenek miktarı

Mekanik özellik açısından bilgi edinmek amacıyla yapılan sertlik testi sonuçları Şekil 6'da verilmiştir. % 0, 3, 6 ve 9 Sm_2O_3 katkısına bağlı olarak sırasıyla sertlikler 179.2, 218.8, 263 ve 318.8 $HV_{0.5}$ olarak ölçülmüştür. Bu değer katkısız Mo matrisine göre sertliğin yaklaşık %77.5 oranında arttığını göstermiştir. Bir malzemenin içinde bulunan gevrek fazlar, kristal yapıdaki kusurlar veya eksik atomlar gibi dislokasyon hareketini engelleyerek malzemenin dayanımını artırabilir. Dislokasyonlar, kristal yapı içinde hareket eden kusurlar veya bozukluklardır ve malzemenin şekil değiştirmesine yol açan mekanik stresler altında hareket ederler. Ancak,

gevrek fazlar bu dislokasyon hareketini engelleyerek malzemenin plastik deformasyonunu sınırlar ve dayanımını artırır. Yapıdaki sert fazlar, malzemenin yük taşıma kapasitesini artırarak sertlikte belirgin bir artışa neden olur. Bu da malzemenin daha dayanıklı olmasını sağlar [11,12].



Şekil 6: Mo-Sm_2O_3 kompozitlerin sertlik grafiği

4. GENEL SONUÇLAR

Toz metalürjisi yöntemiyle üretilen Mo-Sm_2O_3 kompozitlerin mikroyapı, yoğunluk ve sertlik değerlendirmesine üzerine yapılan genel sonuçlar aşağıdaki gibidir.

1) Sm_2O_3 partikülleri kompozit içinde bağıl olarak homojen dağılmıştır. Bunun hem mekanik hem de fiziksel özelliklere olumlu yansıdığı düşünülmektedir

2) Yapıda XRD sonuçlarına göre Mo ve Sm_2O_3 fazları tespit edilmiştir. Herhangi bir oksitlenme meydana gelmemiştir.

3) Sm_2O_3 partiküllerinin ilavesiyle deneysel yoğunluklarda, bağıl yoğunluklarda kısmen azalma olurken, belirli seviyede gözeneklerde artış olmuştur.

4) Sm_2O_3 partiküllerinin Mo matrisine ilavesiyle dislokasyonların kilitlenmesi sonrasında sertliklerde artışlar meydana gelmiştir.

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BAKIR MATRİSLİ KOMPOZİTLERİN GELİŞTİRİLMESİ: BİR LİTERATÜR ÇALIŞMASI

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ÖZET

Titanyum, magnezyum, bakır ve alüminyum gibi metaller, karbürler (silisyum karbür, bor karbür, titanyum karbür vb.), nitrürler (bor nitrür, titanyum nitrür, alüminyum nitrür), oksitler (alüminyum oksit, zirkonyum oksit, titanyum oksit) ve nanopartiküllerle (karbon nanotüp, grafen, karbon nanofiber) bir araya getirilerek metal matris kompozitleri (MMK) meydana getirilir. Bu malzemelerin temel özellikleri arasında artırılmış özgül mukavemet, sertlik, üst düzey aşınma direnci, iyi sönümleme özellikleri, yüksek korozyon direnci ve düşük ağırlık bulunmaktadır. Bakır (Cu) ve bakır alaşım ürünleri, mükemmel elektrik ve ısı iletimi, korozyona karşı gösterdiği dayanıklılık, estetik görünümü ve antimikrobiyal özellikleri sayesinde ısıtma ve soğutma sistemleri, deniz suyunu taşıyan borular ve hem evsel hem de sanayi amaçlı su sistemleri gibi birçok endüstriyel alanda yaygın olarak kullanılmaktadır. Ancak, bu olumlu özelliklerine karşın, saf bakırın sertliği düşüktür, dayanıklılığı zayıftır ve aşınmaya karşı direnci son derece sınırlıdır. Bu sınırlamaların üstesinden gelmek için bakır matrisli MMK üretimi son derece popüler bir konudur. Yukarıda bahsedilen takviyelerin bakır matrisine ilave edildiği MMK'lar döküm, toz metalurjisi, kaplama vb. işlemlerle üretilmektedir. Özellikle toz metalurjisi yöntemlerinden spark plazma sinterleme, seçici lazer sinterleme ve sıcak presleme son teknolojik üretim yöntemleridir. Kaplama yöntemlerinden ise termal sprey kaplamaları yüzey kompozitlerin üretiminde kullanılmaktadır. Buradaki amaç optimum elektriksel ve termal iletkenliğe sahip ve iyileştirilmiş mekanik özelliklere sahip daha kompakt bakır matrisli kompozit malzemelerin geliştirilmesidir.

Anahtar kelimeler: MMK, bakır, kompozitler

DEVELOPMENT OF COPPER-MATRIX COMPOSITES: A LITERATURE REVIEW

ABSTRACT

Titanium, magnesium, copper, and aluminum, carbides (silicon carbide, boron carbide, titanium carbide, etc.), nitrides (boron nitride, titanium nitride, aluminum nitride), oxides (aluminum oxide, zirconium oxide, titanium oxide), and nanoparticles (carbon nanotubes, graphene, carbon nanofibers) are combined to form metal matrix composites (MMCs). The key properties of these materials include increased specific strength, hardness, high wear resistance, good damping properties, high corrosion resistance, and low weight. Copper (Cu) and copper alloy products are widely used in many industrial fields, such as heating and cooling systems, seawater pipes, and domestic and industrial water systems, thanks to their excellent electrical and thermal conductivity, corrosion resistance, aesthetic appearance, and antimicrobial properties. However, despite these positive characteristics, pure copper has low hardness, weak durability, and extremely limited resistance to wear. To overcome these limitations, the production of copper matrix MMCs is an extremely popular topic. MMCs, to which the above-mentioned reinforcements are added to the copper matrix, are produced by processes such as casting, powder metallurgy, and coating. Among powder metallurgy methods, spark plasma sintering, selective laser sintering, and hot pressing are the latest technological production methods. Among coating methods, thermal spray coatings are used to produce surface composites. The objective here is to develop more compact copper matrix composite materials with optimal electrical and thermal conductivity and improved mechanical properties.

Keywords: MMC, copper, composites

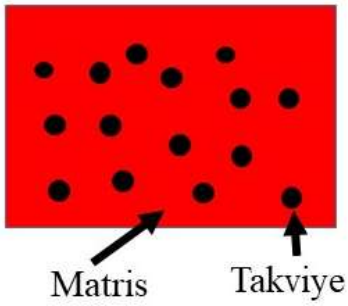
1. GİRİŞ

Bakır ve bakır alaşımları, ticaret metallerinin en önemli kategorilerinden birisini teşkil eder. Harika elektrik ve ısı iletkenlikleri, yüksek korozyon direnci, üretim kolaylığı, iyi dayanıklılıkları ve yorulmaya karşı direnci sayesinde sıkça kullanılırlar. Genelde manyetik özelliğe sahip değillerdir. Rahatlıkla lehimlenebilir ve sert lehim uygulamalarına açıktırlar; birçok bakır ve bakır alaşımı çeşitli gaz, ark ve direnç kaynaklama yöntemleriyle bir araya getirilebilir. Süs eşyaları için, belirli renklerde standart alaşımlar kolaylıkla temin edilebilir. Bakır alaşımları, hemen hemen her türlü doku ve parlaklıkta cilalanıp parlatılabilir. Mevcut kaplama seçeneklerini artırmak amacıyla kaplanabilir, organik malzemelerle kaplanabilir veya kimyasal şekilde renklendirilebilirler [1]. Düşük mukavemet ve zayıf aşınma direnci, Cu ve alaşımlarının en büyük sınırlamasıdır [2].

Bakırın içine herhangi bir alaşım elementi eklendiğinde iletkenliğinin önemli ölçüde düşeceği oldukça iyi bilinmektedir. Gümüş, bakırın iletkenliği üzerinde en az zararlı etkiye sahiptir, ancak gümüş oldukça maliyetlidir. Alaşım elementlerinin sebep olduğu katı çözelti güçlendirmesinin olumsuz etkilerini önlemek adına, bakır bazlı materyallerin mekanik özelliklerini ve aşınma dayanımını artırmak için güçlendirici partiküllerin (dağılım güçlendirmesi) kullanılması iyi bir tercih olmaktadır [3,4]. Bakır matrisli MMK üretmek Cu ve alaşımlarını mukavemetlendirmede etkili bir çözüm olmaktadır.

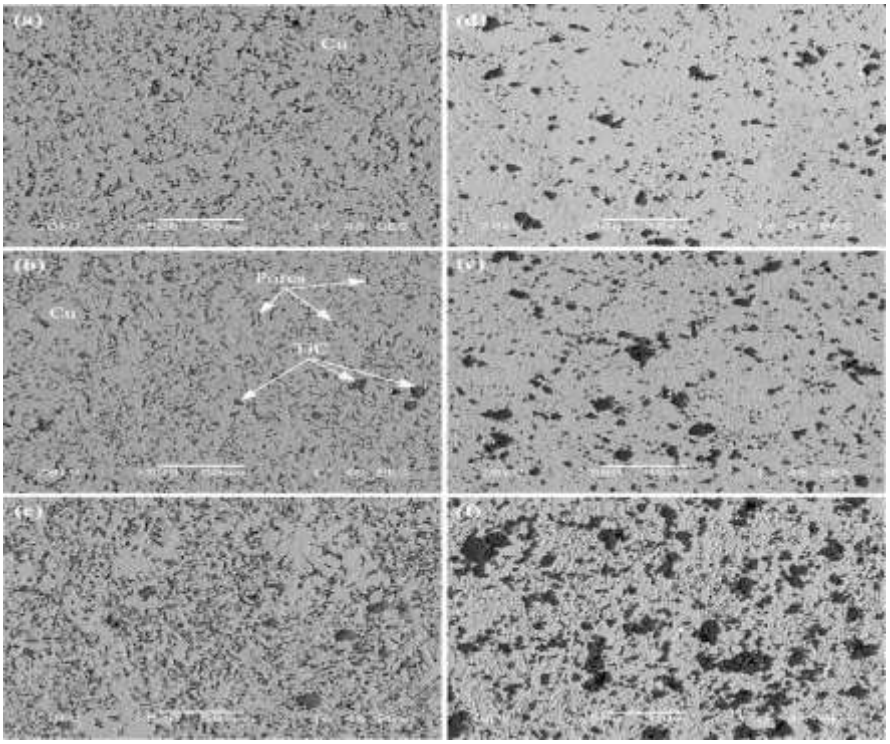
2. BAKIR MATRİSLİ KOMPOZİT MALZEMELER

Matrisin Cu olduğu ve en az iki takviye ile güçlendirilen malzemeler Cu matrisli kompozit malzemelerdir. Cu burada yükün takviyeye iletiminde rol oynarken, takviye ise yükü taşıma vazifesine sahiptir. Şekil 1'de matrisin bakır olduğu basit bir kompozit malzeme gösterimi verilmiştir.

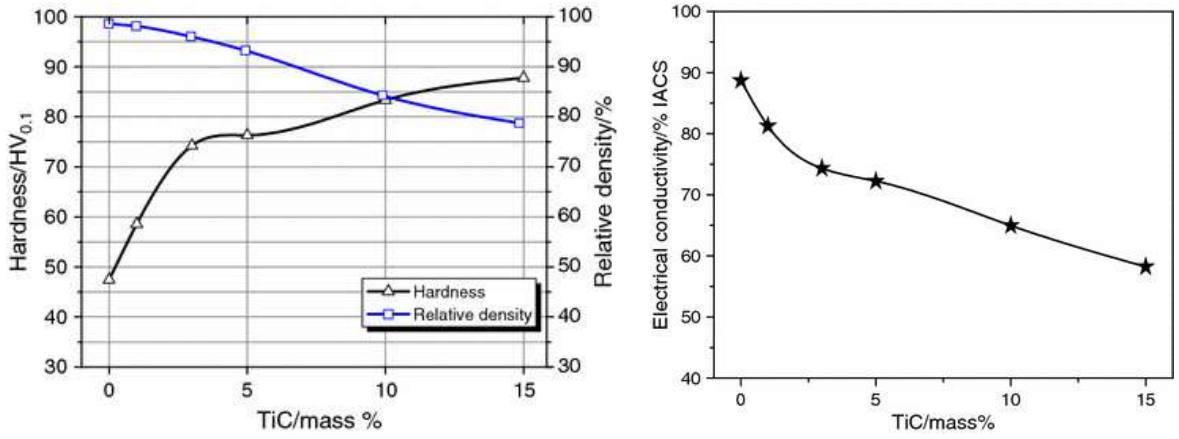


Şekil 1: Kompozit malzeme gösterimi

Literatürde takviyenin şekline ve sayısına bağlı olarak birçok çalışma yapılmıştır. Buytoz vd. [5] sıcak presleme yöntemiyle Cu matrisli TiC takviyeli kompozitleri üretmişler ve mikroyapı ve termal özellikleri incelemişlerdir. Yapılan çalışmada kompozitlerin mikroyapı görüntüleri Şekil 2'de verilmiştir. Mikroyapıda TiC'lerin nispeten homojen dağıldığı görülmüştür. Çalışmada yapılan sertlik ölçümü ve elektriksel iletkenlik ölçümü de Şekil 3'de verilmiştir. TiC takviyesiyle kompozitin güçlendiği görülmüş olup, kısmen de elektriksel iletkenlik düşmüştür.



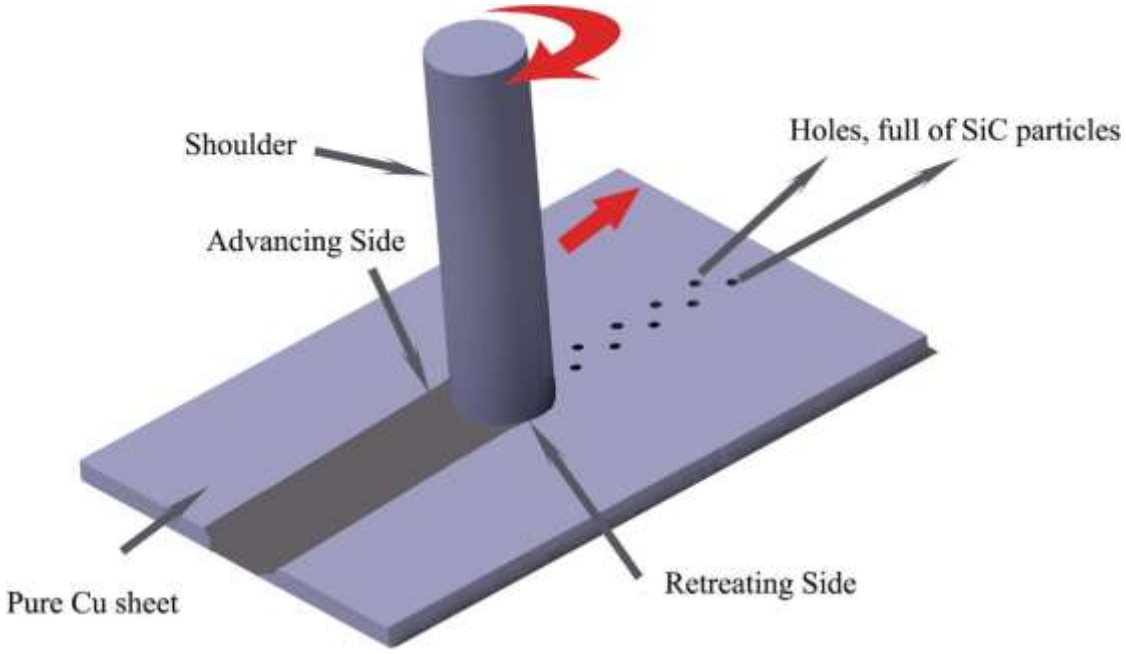
Şekil 2: Cu–TiC kompozitlerinin SEM mikrografları: a) Cu takviyesiz, b) Cu-1 kütle% TiC, c) Cu-3 kütle% TiC, d) Cu-5 kütle% TiC, e) Cu-10 kütle% TiC ve f) Cu-15 kütle% TiC [5].



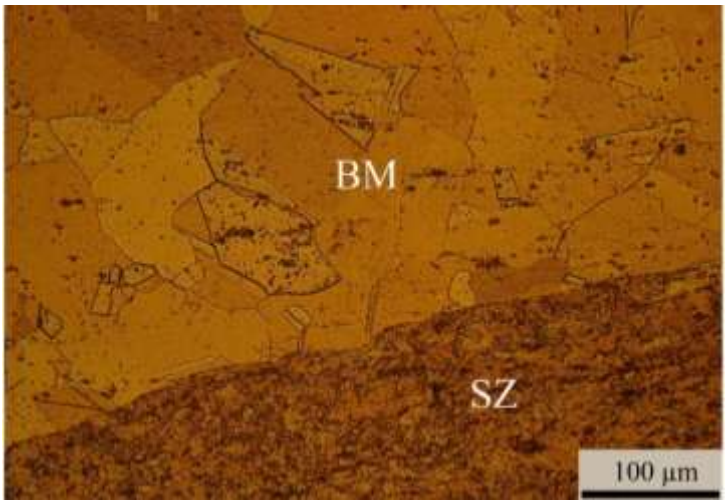
(a) (b)

Şekil 3: (a) Sertlik ve bağıl yoğunluk ve (b) elektriksel iletkenlik [5].

Akramifard vd. [6] sürtünme karıştırma kaynağı (FSP) ile Cu-SiC kompozitleri üretmiştir. İşlem şematiği Şekil 4'de verilmiştir. İnce mikro yapı ve döküm kusurlarının olmaması, FSP'nin başlıca avantajlarıdır. FSP sırasında, özel olarak tasarlanmış pim ve omuzlu döner alet (sarf malzemesi olmayan) plakaya daldırılır ve istenen yönde hareket ettirilir [7]. Üretilen kompozitin mikroyapısı Şekil 5'de verilmiştir.

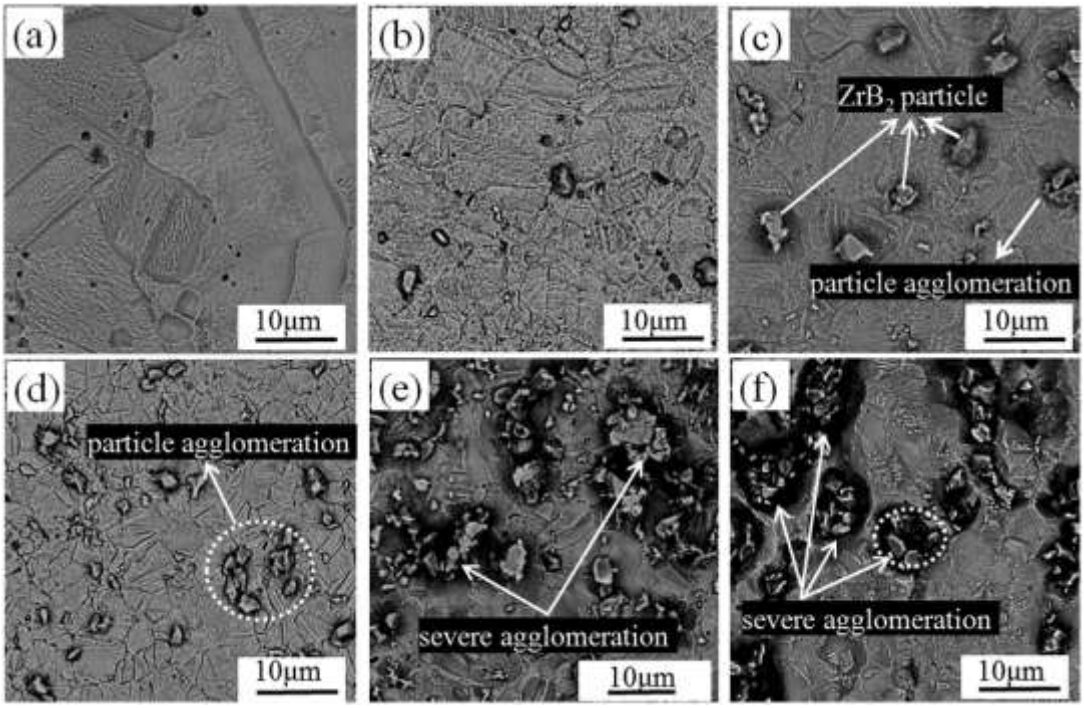


Şekil 4: Pimin hareket ve dönme hareketi ve Cu/SiC'nin imalatı [7].

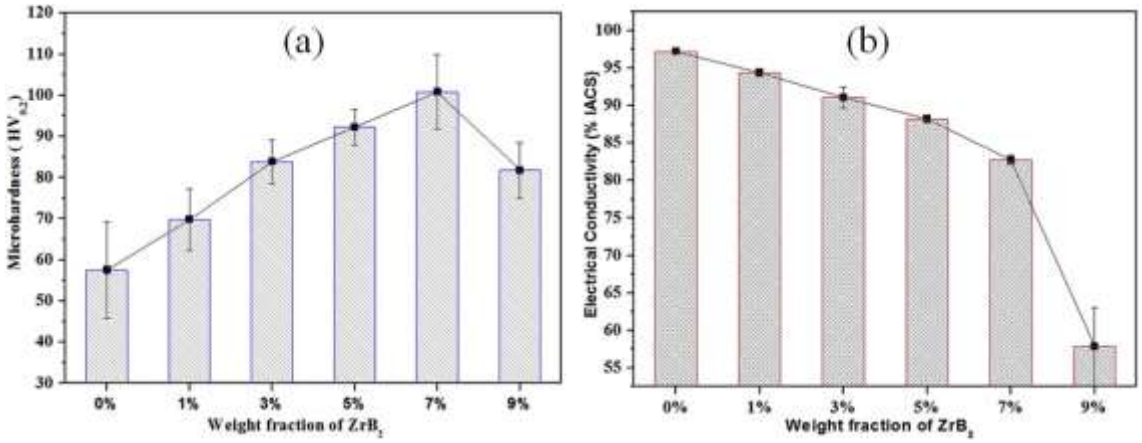


Şekil 5: Esas metal (BM) ve kompozit katman olan stir zone (SZ)'un optik mikroyapısı [7].

Wang vd. [8] sıcak presleme sinterleme tekniği ile Cu-ZrB_2 kompozitlerini üretmişlerdir. Üretilen kompozitlerde ZrB_2'lerin kümeleştiği gözlemlenmiştir (Şekil 6). Belirli bir takviye miktarına kadar sertliğin arttığı, elektriksel iletkenliğin ise belirli bir seviyeye kadar çok fazla düşmediği görülmüştür (Şekil 7).

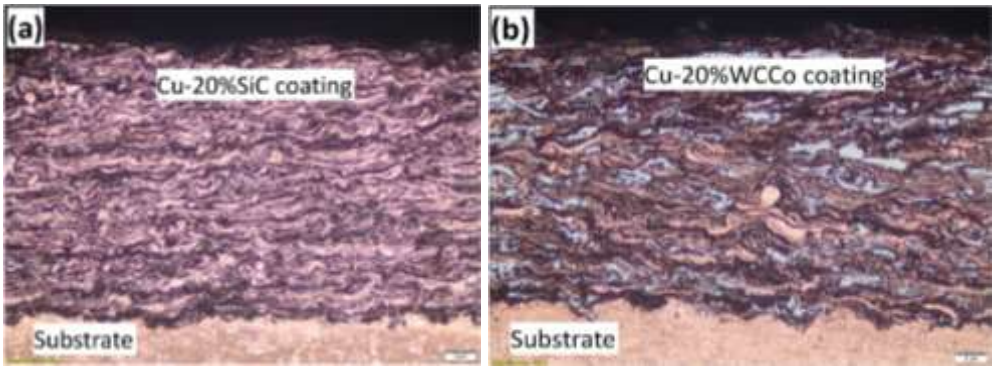


Şekil 6: ZrB_2/Cu kompozitlerinin SEM yüzey morfolojileri: (a) saf Cu, (b) %1,0 ağırlıkça ZrB_2, (c) %3,0 ağırlıkça ZrB_2, (d) %5,0 ağırlıkça ZrB_2, (e) %7,0 ağırlıkça ZrB_2, (f) %9,0 ağırlıkça ZrB_2 [8].

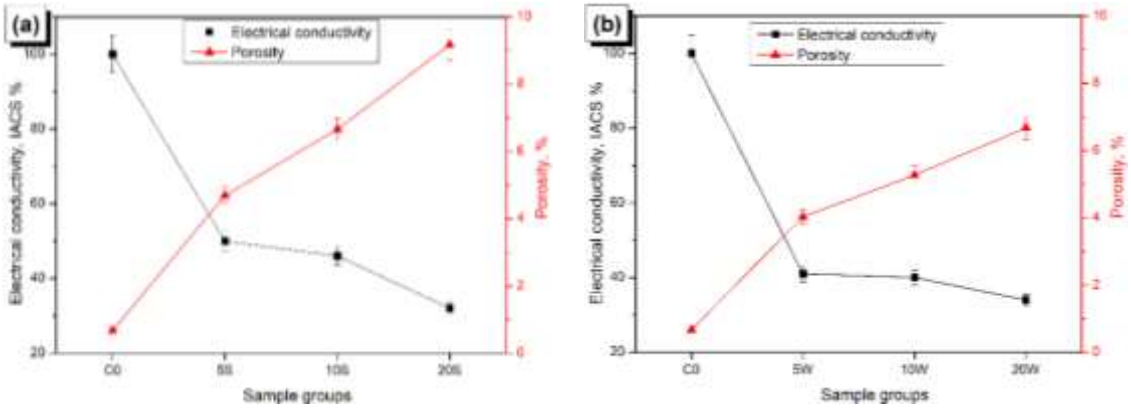


Şekil 7: (a) ZrB_2/Cu kompozitlerinin mikro sertliği ve (b) elektriksel iletkenliği.

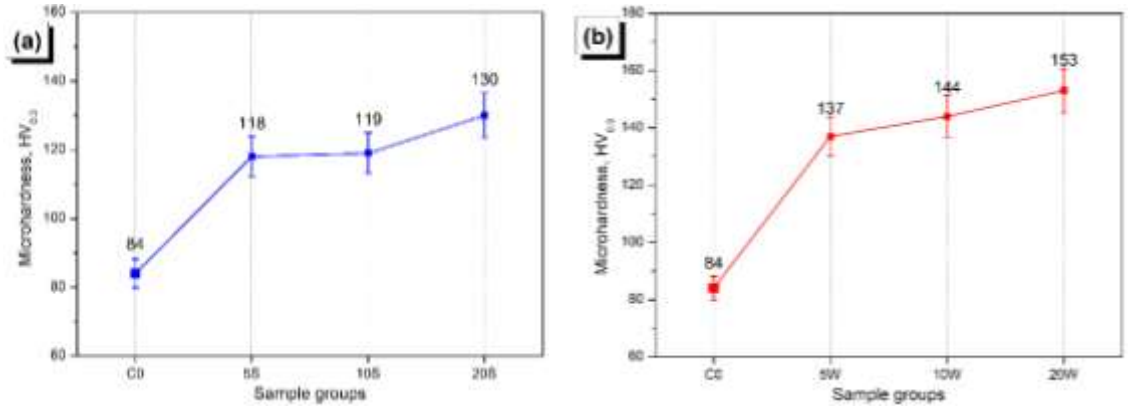
Cu matrisli kompozit malzemeler kaplama katı olarak da literatürde üretilmiştir. Özorak ve Islak [9] plazma püskürtme yöntemi ile Cu alt tabaka yüzeyine uygulanan Cu-SiC/WCCo kompozit kaplamaların mikro yapı, aşınma ve korozyon özellikleri üzerine çalışmışlardır. Matrise eklenen intermetalik fazlar ve seramik partiküller kaplama tabakalarının sertliğini ve aşınma direncini artırırken, elektriksel iletkenliğini azalttığı raporlanmıştır.



Şekil 8: (a) Cu-SiC kaplama ve (b) Cu-WCCo kaplama [9].



Şekil 9: Elektriksel iletkenlik: (a) Cu-SiC kaplama ve (b) Cu-WCCo kaplama [9].

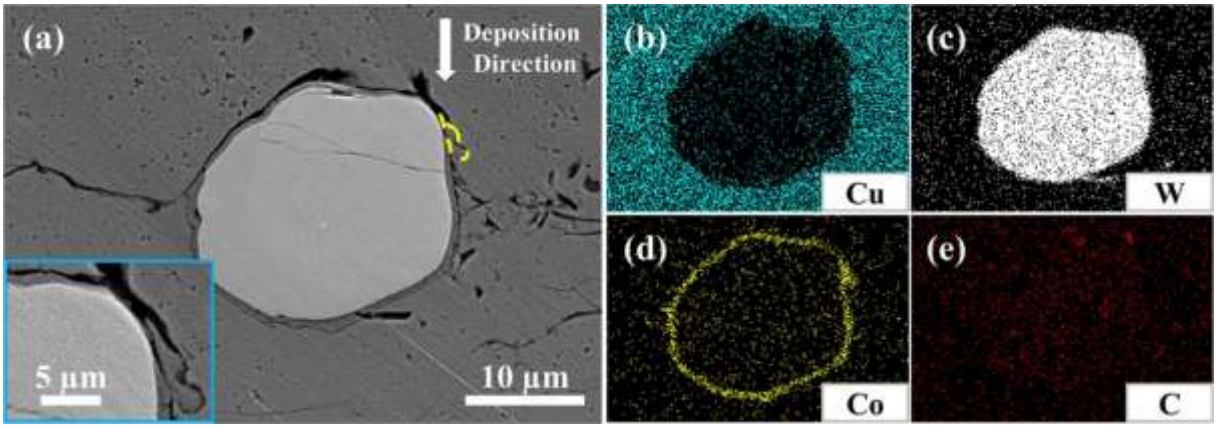


Şekil 10: Sertlik değerleri: (a) Cu-SiC kaplama ve (b) Cu-WCCo kaplama [9].

Ngai vd. [10] sıcak sıkıştırma toz metalurjisi ve kıvılcım plazma sinterleme (SPS) yoluyla Cu–Ti_3SiC_2 metal matris kompozitlerin üretimini analiz etmişlerdir. Çalışma, kompozitlerdeki takviye parçacıklarının 800 °C ve üzeri sıcaklıklarda kararsız olduğunu ve bunun Ti_3SiC_2'nin TiC ve/veya diğer karbürlere ve $TiSi_2$'ye ayrışmasına yol açtığını ortaya koymuştur. Saflığı korumak için işleme sıcaklıkları 750 °C'yi geçmemelidir. 750 °C'de sıcak sıkıştırma ve SPS ile üretilen kompozitler, 950 °C'de sinterlenenlere kıyasla daha düşük yoğunluk sergilerler, ancak elektrik direnç değerleri benzer ve nispeten daha düşüktür.

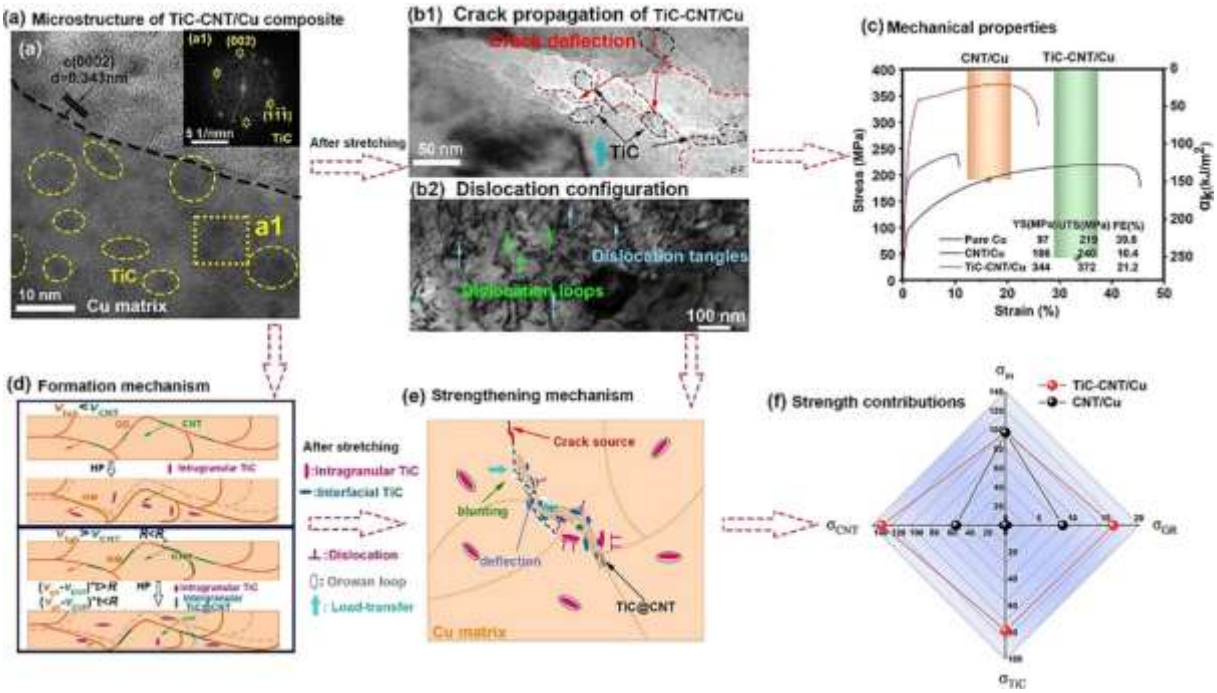
Zhang vd. [11] Q235 çeliği yüzeyinde Cu matrisli CoWC takviyeli kompozitlerini soğuk sprey yöntemiyle üretmişlerdir. %20 ağırlık oranında Co@WC (Cu20(Co@WC)) içeren kaplama, Cu

kaplamasına kıyasla üstün korozyon direnci göstermektedir ve seramik içeriğinin artırılmasıyla daha da geliştirilme potansiyeline işaret etmektedir. Şekil 11'de Cu20(Co@WC) kaplamanın tipik SEM görüntüsü ve EDS haritalaması verilmiştir.



Şekil 11. Cu20(Co@WC) kaplamanın tipik SEM görüntüsü ve EDS haritalaması [11].

Feng vd. [12] CNT ve yerinde intragranüler TiC'nin çift nanofazı ile takviye edilmiş Cu matris kompozitinde mukavemet-süneklik dengesinin sağlanması üzerine çalışmışlardır. Sonuçlar, CNT yüzeyindeki arayüzey TiC'nin epitaksiyel büyümesini (yani, CNT(0002)//TiC(200)) ve TiC ile Cu matrisi arasında yarı tutarlı bir arayüzün oluşumunu ortaya koydu; bu, arayüzey bağlanma mukavemetini etkili bir şekilde artırabilir ve CNT'nin yük transfer verimliliğini optimize edebilir.



Şekil 12. TiC-CNT/Cu kompozit malzemenin mikromorfolojisi ve güçlendirme mekanizmalarının şematik diyagramı [12].

3. GENEL SONUÇLAR

Titanyum, magnezyum, bakır, alüminyum, karbürler, nitrürler, oksitler ve nanopartiküller, artırılmış mukavemet, sertlik, aşınma direnci ve korozyon direnci gibi gelişmiş özelliklere sahip metal matrisli kompozitler (MMC'ler) oluşturmak için kullanılır. Bakır ve alaşımları, mükemmel elektriksel ve termal iletkenlikleri nedeniyle çeşitli endüstrilerde yaygın olarak kullanılır, ancak saf bakırın düşük sertlik ve dayanıklılık gibi sınırlamaları vardır. Bu sorunları gidermek için, daha iyi iletkenlik ve mekanik özellikler elde etmeyi amaçlayan döküm, toz metalurjisi (kıvılcım plazma sinterleme ve sıcak presleme dahil) ve termal püskürtme ve soğuk sprey kaplamaları gibi yöntemler kullanılarak bakır matrisli MMC'ler geliştirilmektedir.

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ANTİMİKROBİYAL PEPTİTLER: YAPISAL ÇEŞİTLİLİK, MEKANİZMALAR VE KLİNİK PERSPEKTİFLER

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ÖZET

Antimikrobiyal peptitler (AMP'ler), küresel ölçekte artan antimikrobiyal direnç (AMR) sorununa karşı umut vadeden biyolojik moleküller arasında yer almaktadır. Doğal bağışıklık sisteminin evrimsel olarak korunmuş bileşenleri olan AMP'ler; bakteri, mantar, virüs ve parazitlere karşı geniş spektrumlu aktivite göstermektedir. Amfipatik ve katyonik yapıları, mikrobiyal zarları seçici biçimde hedef alarak konak hücrelerine zarar vermeden etkili olmalarını sağlar. Yapısal olarak α-sarmal, β-tabaka, prolin açısından zengin, uzamış (lineer) ve halkasal formlar olmak üzere farklı konformasyonlar sergileyen AMP'ler, bu çeşitlilik sayesinde farklı etki mekanizmaları ve biyolojik dayanıklılıklar göstermektedir.AMP'ler yalnızca doğrudan antimikrobiyal etkilere sahip olmayıp, aynı zamanda immünmodülatör ve yara iyileştirici özellikleriyle de dikkat çekmektedir. Bu nedenle "konak savunma peptitleri" (HDP'ler) olarak da tanımlanmaktadır. Son yıllarda (2020–2025) AMP'lerin yapı–aktivite ilişkileri üzerine yapılan çalışmalar, kimyasal olarak modifiye edilmiş türevlerin geliştirilmesini ve farmakolojik özelliklerinin iyileştirilmesini sağlamıştır. D-amino asit ikamesi, halkalaşma ve lipidilasyon gibi yapısal düzenlemeler; proteolitik yıkıma karşı dayanıklılığı, biyoyararlanımı ve terapötik etkinliği artırmaktadır. Klinik olarak Brilacidin**,** Pexiganan**,** Omiganan**,** Novexatin **ve** Iseganan gibi AMP temelli adaylar; bakteriyel deri enfeksiyonları, diyabetik ülserler, mukozit ve fungal enfeksiyonlara karşı olumlu sonuçlar göstermektedir. Ayrıca, AMP'ler çevre dostu ve biyolojik olarak parçalanabilir özellikleri sayesinde tarım, veterinerlik ve biyomalzeme mühendisliği gibi farklı alanlarda da potansiyel uygulama alanı bulmaktadır. Bununla birlikte, in vivo kararlılık, sitotoksisite ve yüksek üretim maliyetleri AMP'lerin geniş ölçekli kullanımı önündeki temel engellerdir. Peptit optimizasyonu, formülasyon geliştirme ve kontrollü salım sistemleri üzerine yürütülen

çalışmalar bu sınırlamaların aşılmasına katkı sağlayacaktır. Genel olarak AMP'ler, antibiyotik direncine karşı yeni nesil antimikrobiyal ve immünmodülatör ajanlar olarak önemli bir araştırma ve uygulama potansiyeline sahiptir.

Anahtar Kelimeler: Antimikrobiyal peptitler, antibiyotik direnci, yapı-aktivite ilişkisi, biyoteknoloji, klinik uygulamalar.

ANTIMICROBIAL PEPTIDES: STRUCTURAL DIVERSITY, MECHANISMS, AND CLINICAL PERSPECTIVES

ABSTRACT

Antimicrobial peptides (AMPs) represent a promising class of bioactive molecules with significant potential to address the global crisis of antimicrobial resistance (AMR). As evolutionarily conserved components of innate immunity, AMPs display broad-spectrum activity against bacteria, fungi, viruses, and parasites. Their amphipathic and cationic nature allows selective disruption of microbial membranes while preserving host cell integrity. Structurally, AMPs encompass diverse conformations—including α-helical, β-sheet, proline-rich, extended, and cyclic forms—each contributing to distinct mechanisms of action and biological stability. Beyond their direct antimicrobial effects, AMPs exert crucial immunomodulatory and wound-healing functions, acting as multifunctional host defense peptides (HDPs). Recent research (2020–2025) has expanded the understanding of AMP structure–activity relationships and enabled the development of chemically modified analogues with enhanced pharmacological properties. Modifications such as D-amino acid incorporation, cyclization, and lipidation improve peptide stability, resistance to proteolytic degradation, and therapeutic efficacy. Currently, several AMPs are advancing through clinical development, including Brilacidin, Pexiganan, Omiganan, Novexatin, and Iseganan, which demonstrate promising results against bacterial and fungal infections as well as inflammation-related disorders. In addition to their medical applications, AMPs have potential uses in agriculture, veterinary medicine, and biomaterial engineering as eco-friendly and biocompatible antimicrobial agents. Despite these advances, challenges such as limited in vivo stability, cytotoxicity, and high production costs remain obstacles to their widespread implementation. Ongoing efforts in peptide optimization, formulation, and delivery systems are expected to overcome these barriers. Overall, AMPs hold great promise as next-generation anti-infective and immunomodulatory agents, offering an innovative strategy to combat the increasing prevalence of antibiotic-resistant pathogens.

Keywords: Antimicrobial peptides, antibiotic resistance, structure–activity relationship, biotechnology, clinical applications.

INTRODUCTION

The global escalation of antibiotic-resistant pathogens constitutes one of the most pressing threats to human health in the 21st century. Bacterial strains such as Methicillin-resistant Staphylococcus aureus (MRSA), Pseudomonas aeruginosa, and Klebsiella pneumoniae have developed multidrug resistance, rendering conventional antibiotics increasingly ineffective (Ventola, 2015). The World Health Organization (WHO) has declared antimicrobial resistance (AMR) a top global priority, warning that without new interventions, routine infections and surgical procedures may become life-threatening. Against this backdrop, antimicrobial peptides (AMPs) have emerged as promising candidates to bridge the widening gap in the antibiotic discovery pipeline. AMPs are evolutionarily conserved molecules that play a central role in innate immunity across bacteria, plants, invertebrates, and vertebrates. Since their discovery in the early 1980s—beginning with cecropins from insects and defensins from mammals—AMPs have been recognized for their broad-spectrum antimicrobial activity and their rapid, non-specific mode of action (Bahar & Ren, 2013). Unlike traditional antibiotics that target specific metabolic pathways, AMPs primarily act by disrupting microbial membranes through electrostatic interactions. Their cationic and amphipathic nature allows selective binding to negatively charged bacterial membranes while sparing host eukaryotic cells, thereby minimizing cytotoxicity (Boparai & Sharma, 2020).

Over the past two decades, extensive biochemical and structural studies have revealed that AMPs possess multifunctional properties extending beyond direct microbial killing. They modulate host immune responses, promote tissue repair, and exhibit antiviral and anticancer activities (Hemshekhar et al., 2016). In addition, advances in high-throughput sequencing and computational peptide design have accelerated AMP discovery, contributing to the identification of more than 3,500 unique peptides cataloged in databases such as APD3. These developments underscore the translational promise of AMPs as next-generation therapeutics capable of addressing the global antimicrobial crisis. As the scientific community intensifies efforts to combat AMR, the study of AMPs continues to offer critical insights into both fundamental biology and innovative therapeutic design(Fjell et al., 2012).

STRUCTURAL DIVERSITY OF AMPS

Antimicrobial peptides (AMPs) represent one of the most structurally diverse groups of biomolecules in nature. Their architecture is intimately linked to their function, influencing membrane affinity, stability, and specificity toward microbial targets. Based on secondary structure and physicochemical characteristics, AMPs can be broadly classified into four major groups: α-helical, β-sheet, extended (linear or flexible), and cyclic peptides. This structural diversity reflects their evolutionary adaptation to diverse ecological niches and microbial threats (Koehbach & Craik, 2019). α-helical peptides, exemplified by LL-37 (human cathelicidin) and magainins (from amphibians), adopt amphipathic α-helices upon interaction with lipid membranes. Their amphipathic nature—featuring segregated hydrophobic and hydrophilic faces—allows them to insert into microbial membranes and form transient pores. The helical conformation often arises only in membrane-mimicking environments, underscoring the role of lipid interactions in peptide folding (Rosengren et al., 2002). These peptides typically display rapid, non-specific lytic activity against a broad range of bacteria, fungi, and viruses. β-sheet peptides, such as mammalian defensins and porcine protegrins, contain multiple cysteine residues forming disulfide bridges that stabilize their tertiary structure. This configuration imparts exceptional resistance to thermal and enzymatic degradation (Bowerman & Nilsson, 2012). Beyond antimicrobial action, β-sheet peptides are also known for immunomodulatory functions, including chemotactic activity and regulation of

cytokine release. Because of their conformational rigidity, β-sheet AMPs exhibit high selectivity but may show reduced activity in lipid-rich environments compared to α-helical types. Proline-rich AMPs (PR-AMPs) form a distinctive subclass primarily found in insects, such as apidaecins, drosocins, and oncocins. Unlike membrane-active peptides, PR-AMPs penetrate bacterial cells and interact with intracellular targets, notably ribosomal subunits or the heat shock protein DnaK, thereby inhibiting protein synthesis. Their mechanism is highly specific, leading to bacteriostatic rather than bactericidal effects. This unique intracellular mode of action has sparked interest in their development as antibiotics against multidrug-resistant Gram-negative bacteria (Mishra et al., 2018). Extended or unstructured peptides, including indolicidin and histatins, lack a stable secondary structure in aqueous solution but adopt defined conformations upon membrane interaction. These peptides are rich in aromatic residues such as tryptophan and proline, which facilitate insertion into microbial membranes and binding to nucleic acids. Their flexibility enables adaptation to different lipid environments, broadening their spectrum of activity (Rath et al., 2005). Cyclic peptides, such as plant-derived cyclotides and primate θ-defensins, represent the most stable AMP class due to head-to-tail cyclization and multiple disulfide linkages. This cyclic backbone confers extraordinary resistance to proteolytic degradation, extreme pH, and temperature variations, making them ideal scaffolds for therapeutic engineering. Cyclotides, for instance, are being investigated as oral peptide drugs owing to their inherent stability in the gastrointestinal tract (Ji et al., 2024). Recent advances in structural biology—particularly NMR spectroscopy and X-ray crystallography—have provided detailed insights into AMP conformations, self-association, and membrane interactions (Haney et al., 2019). These studies reveal that structure-function relationships are far from uniform; even small amino acid substitutions can profoundly alter activity, selectivity, and toxicity. Consequently, rational design of synthetic AMPs increasingly relies on computational modeling and molecular dynamics simulations to optimize peptide architecture for desired biological effects. Together, the structural plasticity and biochemical versatility of AMPs underpin their wide-ranging potential as novel therapeutics in the post-antibiotic era (Table 1).

Table 1: Structural Classes of Antimicrobial Peptides

Structural Class	Representative Peptides	Key Features
α-helical	LL-37, Magainin	Linear, amphipathic, disrupt membranes
β-sheet	Defensins, Protegrins	Disulfide bonds, immune modulation
Proline-rich	Apidaecin, Drosocin	Intracellular targets, protein synthesis inhibition
Cyclic	Cyclotides, θ-defensins	High stability, protease resistance

MECHANISMS OF ACTION

AMPs neutralize pathogens through a combination of physical disruption and biochemical interference, making them among the most versatile molecules in innate immunity. Their mechanisms of action can be broadly classified into membrane-targeting and non-membrane-targeting pathways, although many peptides exhibit overlapping modes that depend on concentration, environment, and microbial membrane composition (Shai, 2002).

Membrane-Targeting Mechanisms

The most recognized activity of AMPs is their ability to interact directly with microbial membranes, which are typically rich in negatively charged phospholipids such as phosphatidylglycerol and cardiolipin. This contrasts with the zwitterionic nature of mammalian cell membranes, enabling AMPs to discriminate between host and pathogen cells (Huang & Li, 2025). Upon approaching the bacterial surface, electrostatic attraction facilitates peptide binding and accumulation on the membrane, leading to permeabilization via several distinct models:

Barrel-Stave Model

Peptides such as alamethicin insert perpendicularly into the membrane, forming transmembrane pores where hydrophobic residues interact with lipids and hydrophilic residues line the pore lumen (Murray et al., 2016).

Toroidal Pore Model

Observed in magainins and melittin, this model involves peptide-induced curvature where lipid headgroups bend inward to form mixed peptide–lipid pores, leading to ion leakage (Sengupta et al., 2008).

Carpet Model

Peptides align parallel to the membrane surface, covering it like a "carpet." At critical concentrations, they disrupt bilayer integrity, resulting in micellization and complete membrane dissolution (Shai, 2002). These physical disruptions rapidly lead to loss of membrane potential, leakage of cytoplasmic contents, and cell death within minutes. Importantly, such mechanisms are non-specific to biochemical targets, minimizing the probability of resistance development—a key advantage over conventional antibiotics (Lazzaro et al., 2020).

Non-Membrane Mechanisms

Beyond their membrane activity, many AMPs exert intracellular effects after translocation into microbial cells. Proline-rich AMPs (PR-AMPs), such as apidaecin and drosocin, inhibit protein synthesis by binding to bacterial ribosomes or the chaperone protein DnaK, blocking post-translational folding of nascent polypeptides (Scocchi et al., 2016). Other AMPs target essential enzymatic pathways or interfere with DNA and RNA synthesis, leading to replication arrest. Indolicidin, for instance, binds DNA through intercalation, while histatins in saliva generate reactive oxygen species that compromise mitochondrial activity in fungal pathogens (Mansour et al., 2014).

Immunomodulatory and Signaling Functions

In addition to their direct antimicrobial effects, antimicrobial peptides (AMPs) function as key immunomodulatory molecules within the host defense system. Peptides such as LL-37 and β-defensins activate chemokine receptors including CCR6 and FPR2, thereby promoting the recruitment of neutrophils, macrophages, and dendritic cells to sites of infection (Mookherjee et al., 2020). They also modulate cytokine networks by suppressing pro-inflammatory mediators like TNF-α and IL-1β, while enhancing anti-inflammatory cytokines such as IL-10. Owing to their dual ability to kill pathogens and orchestrate immune responses, AMPs are often referred to as "host defense peptides" (Hancock, 2000). Beyond immunomodulation, they contribute to wound healing by stimulating angiogenesis and promoting keratinocyte migration.

Across a wide range of species—from insects to humans—epithelial cells synthesize AMPs and related polypeptides as central effector molecules of the innate immune response (Zasloff,

2002). These peptides exhibit broad-spectrum activity against bacteria, viruses, and fungi, and also play a role in regulating the natural microbiota (Boman, 2000). In human skin, four major AMPs have been identified: the β-defensins hBD-1, hBD-2, hBD-3 (Harder et al., 1997), and the sole human cathelicidin, hCAP-18. The active C-terminal fragment of hCAP-18, consisting of 37 amino acids, is known as LL-37 (Frohm et al., 1997). Chronic wounds often fail to heal due to the presence of multispecies pathogenic biofilms, which protect bacteria from immune clearance and certain antibiotics. LL-37, with its combined anti-biofilm, antimicrobial, and immunomodulatory properties, can circumvent many of these challenges, and its topical application offers advantages by avoiding barriers associated with systemic peptide delivery (Duplantier & van Hoek, 2013).

Combined and Synergistic Effects

Recent studies have revealed that AMPs often work synergistically—either with other peptides or conventional antibiotics—to enhance antimicrobial efficacy and overcome biofilm-associated tolerance. For example, combining AMPs with β-lactams or aminoglycosides can restore drug sensitivity in resistant bacterial strains. This multifaceted activity, encompassing physical disruption, intracellular inhibition, and immune modulation, underscores the unique therapeutic promise of AMPs as multifunctional agents capable of addressing diverse infectious challenges while reducing the emergence of resistance (Haney et al., 2019).

LITERATURE TRENDS AND ADVANCES (2020–2025)

Between 2020 and 2025, antimicrobial peptide (AMP) research has experienced exponential growth, reflecting the urgent global need for new therapeutic strategies against antibiotic-resistant infections. Bibliometric analyses of databases such as PubMed, Scopus, and Web of Science show a steady increase in AMP-related publications, particularly in the fields of computational peptide design, synthetic biology, and translational medicine (Agüero-Chapin et al., 2022). The COVID-19 pandemic further accelerated this research momentum by emphasizing the demand for broad-spectrum antivirals and immunomodulatory agents, areas in which AMPs have demonstrated considerable promise (Ramazi et al., 2022). A major trend in recent years is the integration of artificial intelligence (AI) and machine learning (ML) into peptide discovery. Using predictive algorithms, researchers can now design de novo peptides with optimized antimicrobial potency, selectivity, and reduced cytotoxicity. Databases such as DBAASP, APD3, and CAMP R4 have been enriched with structural and activity data, providing large-scale datasets for AI-driven models. Computational pipelines combining molecular dynamics simulations and neural network analysis have enabled in silico screening of thousands of peptide analogues before experimental validation (Veltri et al., 2018). These tools have dramatically shortened the drug development timeline and lowered the cost of AMP optimization.mParallel to computational advances, chemical and hybrid peptide engineering has produced a new generation of AMPs with improved pharmacokinetic profiles. Strategies such as D-amino acid substitution, peptide cyclization, and lipidation enhance proteolytic resistance and membrane affinity. Hybrid constructs that fuse AMP motifs with polymeric or nanoparticle carriers have been shown to increase bioavailability and tissue penetration (Wang & Li, 2016). Moreover, peptidomimetics—synthetic analogues that mimic AMP structure and charge distribution—are emerging as stable, cost-effective alternatives suitable for large-scale production.

Clinically, the translation of AMPs from bench to bedside is steadily progressing. As of 2025, more than 40 peptide-based antimicrobials are under active preclinical or clinical evaluation. Among them, Brilacidin and Pexiganan are leading candidates that have reached Phase II–III trials for bacterial skin infections, oral mucositis, and even COVID-19-related inflammatory

complications (Mookherjee et al., 2020). Omiganan has shown efficacy as a topical treatment for catheter-associated infections, while Novexatin targets fungal onychomycosis with favorable safety outcomes. Notably, the antimicrobial peptide Iseganan has been tested for oral mucositis prevention in cancer therapy patients, reflecting diversification into supportive care settings (Cresti et al., 2024). The field has also seen growing interest in multifunctional AMPs that exhibit antibacterial, antiviral, antifungal, and anticancer activities. Several studies highlight AMPs' dual role as immunomodulators—capable of enhancing cytokine balance, promoting wound healing, and modulating inflammatory pathways (Lazzaro et al., 2020). These findings have reshaped the perception of AMPs from purely bactericidal molecules to host defense peptides (HDPs) with systemic physiological relevance. Finally, a noteworthy trend in recent literature is the emergence of bioinformatics-driven AMP taxonomy and structure–activity relationship (SAR) analyses. Researchers are now classifying AMPs not only by structure but also by mechanism, sequence motif, and spectrum of activity. Phylogenetic studies indicate convergent evolution of AMP families across kingdoms, suggesting strong selective pressure to maintain antimicrobial function despite sequence divergence. Collectively, the 2020–2025 period has been transformative, characterized by technological convergence, expanding clinical validation, and a paradigm shift toward personalized and precision peptide therapeutics (Reyes et al., 2024) (Table 2).

Table 2. Selected AMPs in Clinical or Preclinical Development

Peptide Name	Therapeutic Target	Clinical Status
Omiganan	Catheter-related infections	Phase III completed
Pexiganan	Diabetic foot ulcers	Phase III ongoing
Brilacidin	Bacterial skin infections, COVID-19	Phase II/III
Novexatin	Onychomycosis	Phase II
Iseganan	Oral mucositis prevention	Phase II completed

THERAPEUTIC AND INDUSTRIAL APPLICATIONS

AMPs are increasingly explored for medical, veterinary, and agricultural applications due to their potent antimicrobial and immunomodulatory properties. Clinically, they are being developed as topical antimicrobials, systemic anti-infectives, and anti-biofilm coatings for medical implants (Lazzaro et al., 2020). The rapid emergence of antibiotic-resistant pathogens has intensified the search for alternative therapeutics, placing AMPs among the most promising candidates (Sobanbua et al., 2020). Their broad-spectrum activity and effective defense mechanisms against diverse microbes make them strong potential substitutes for conventional antibiotics (Van Der Weide et al., 2020). Unlike many traditional antibiotics, which often act bacteriostatically, AMPs typically exert rapid bactericidal effects (Wang et al., 2020). Among the numerous AMPs produced by the human body, cathelicidins and defensins are the most extensively studied. Several naturally occurring AMPs have progressed toward therapeutic use for conditions including oral mucositis, cystic fibrosis–associated lung infections, cancer, and topical skin infections (Wang et al., 2020). Cathelicidins demonstrate antibacterial activity against pathogens such as Group A Streptococcus, Escherichia coli, Group B Streptococcus, and Staphylococcus aureus, while defensins—classified as α- and β-defensins—have shown antiviral effects against adenovirus, influenza virus, herpesvirus, and papillomavirus in vitro (Sader et al., 2020). In dermatology, research increasingly focuses on the role of AMPs in

conditions such as atopic dermatitis and psoriasis, where they help prevent secondary infections (Sader et al., 2020). These findings collectively support the growing interest in AMPs as next-generation anti-infective therapeutics. In agriculture, synthetic pesticides have long been used to control plant diseases and insect pests; however, their extensive application has raised concerns regarding environmental and human health. As a result, AMPs—particularly those derived from plants—are gaining attention as low-toxicity, natural, and highly effective antimicrobial agents. Many plant AMPs are encoded by genes expressed at low basal levels but strongly upregulated upon pathogen attack. Following pathogen stimulation, multiple AMPs can be simultaneously produced in different organs of the same plant (Mith et al., 2015). Plant AMPs typically target pathogens in a nonspecific manner, making it difficult for microbes to develop resistance, which enhances their suitability for improving disease resistance in crops (Goyal & Mattoo, 2014). Beyond pathogen defense, plant AMPs also participate in regulating plant growth and development, and several have shown beneficial therapeutic effects in human disease models. Structural features—including amino acid composition, net charge, hydrophobicity, amphipathicity, and folding tendencies—collectively influence AMP antimicrobial potency and specificity. With broad potential applications in agriculture, food preservation, breeding technologies, and medicine, plant-derived AMPs are now recognized as promising alternatives to conventional antibiotics (Tang et al., 2018).

CHALLENGES AND FUTURE DIRECTIONS

AMPs are expected to become widely used in the near future as significant alternatives due to the growing problem of antibiotic resistance in bacteria (Aguilar-Toalá et al., 2020). Their ability to exhibit strong activity at minimal concentrations, their cost-effectiveness, and their broad-spectrum mechanisms of action make them promising candidates for expanded use across many sectors, from food to textiles (Chelliah et al., 2020). Although the therapeutic and industrial applications of AMPs are rapidly expanding, several major challenges still hinder their widespread clinical and commercial adoption, including production costs, stability issues, rapid degradation by serum proteases, and pharmacokinetic limitations that arise in large-scale applications (Mahlapuu et al., 2016). The structural heterogeneity of AMPs can lead to high efficacy against specific target organisms while resulting in reduced performance against others, increasing the need for rational design and optimization studies (Fjell et al., 2012). One of the most significant barriers to clinical use is the inability to completely eliminate host toxicity and the resulting narrow therapeutic window; therefore, peptide engineering and formulation strategies aimed at reducing toxicity in both natural and synthetic derivatives have gained substantial importance (Mookherjee et al., 2020). Another limiting factor is the loss of activity in physiological environments with high salt and serum content, largely due to weakened membrane interactions, making peptide optimization and appropriate carrier/formulation strategies essential (Haney & Hancock, 2013). Nevertheless, advances in artificial intelligence and computational methods are expected to accelerate AMP discovery and optimization, and rational design strategies coupled with nanocarriers are anticipated to enable the development of more stable, less toxic, and therapeutically superior AMPs (Szymczak & Szczurek, 2023). Beyond medical applications, AMPs are also expected to gain importance in agriculture as biocontrol agents and potential biopesticides; notably, insect- and plant-derived peptides may provide dual protection by exhibiting both antimicrobial and insecticidal effects while triggering induced systemic resistance mechanisms in plants (Dho et al., 2023). Peptides derived from Bacillus species have demonstrated antimicrobial activity against phytopathogens and, in some cases, toxicity against insects, offering environmentally friendly alternatives for integrated pest management and attracting growing research interest in this field (Ajuna, 2024). Molecular engineering approaches—such as cyclization, the incorporation of D-amino acids,

and terminal modifications—combined with nanotechnological carriers that provide controlled release represent some of the most promising strategies to enhance AMP stability and efficacy in agricultural field applications (Brizuela et al., 2025). Despite these promising developments, several issues remain unresolved under field conditions, including UV stability, interactions with proteases on soil and plant surfaces, and economically sustainable large-scale production. Therefore, successful implementation of AMPs in agriculture and medicine will require the parallel advancement of interdisciplinary research and regulatory standardization (Mahlapuu et al., 2016; Dho et al., 2023).

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TARIMSAL ÜRETİM VE ZARARLI YÖNETİMİNDE BOR VE BOR BİLEŞİKLERİNİN ROLÜ

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ÖZET

Bor (B), bitkilerin sağlıklı büyüme, gelişme ve üreme süreçlerinin sürdürülebilmesi için gerekli olan temel mikro besin elementlerinden biridir. Bitki fizyolojisinde çok yönlü görevler üstlenen bor; hücre duvarı biyosentezi, zar bütünlüğünün korunması, karbonhidrat ve enerji metabolizması, lignin sentezi, azot ve fenolik bileşiklerin taşınımı, polen tüpü uzaması ve döllenme süreçlerinde kritik rol oynar. Bor eksikliği durumunda, hücre bölünmesi ve uzaması aksar; kök gelişimi yavaşlar, çiçeklenme ve meyve tutumu azalır, dokularda nekrotik lekeler ve deformasyonlar görülür. Bu durum, bitkisel verim ve kalite kayıplarına neden olurken; aşırı bor birikimi ise toksik etki göstererek yapraklarda kloroz, nekroz ve büyüme duraklaması gibi olumsuzluklara yol açabilir. Bu nedenle, toprakta ve bitki dokularında optimal bor dengesinin korunması, sürdürülebilir tarımsal üretim için büyük önem taşımaktadır. Beslenmedeki fizyolojik işlevlerinin yanı sıra, bor ve bor içeren bileşikler – özellikle **borik asit** ve **boratlar** – son yıllarda **insektisidal ve antimikrobiyal özellikleri** nedeniyle dikkat çekmektedir. Bu bileşiklerin, böceklerin beslenme davranışlarını, enzim aktivitelerini ve fizyolojik dengelerini bozarak ölümle sonuçlanan etkiler oluşturduğu bildirilmiştir. Ayrıca bor bileşikleri, hedef dışı organizmalara düşük toksisite göstermeleri, çevrede kalıntı bırakmamaları ve biyolojik olarak parçalanabilir olmaları nedeniyle çevre dostu pestisit alternatifleri arasında değerlendirilmektedir. Bor temelli bitki besleme ve zararlı yönetimi yaklaşımlarının entegre edilmesi, kimyasal insektisit kullanımını azaltarak çevreye duyarlı, güvenli ve sürdürülebilir tarım sistemlerinin geliştirilmesine katkı sağlayabilecek yenilikçi bir strateji olarak öne çıkmaktadır.

Anahtar Kelimeler: Bor, borik asit, tarımsal üretim, zararlı yönetimi, sürdürülebilir tarım

ROLE OF BORON AND BORON COMPOUNDS IN CROP PRODUCTION AND INSECT PEST MANAGEMENT

ABSTRACT

Boron (B) is an essential micronutrient required for maintaining healthy plant growth, development, and reproduction. It plays versatile roles in plant physiology, including cell wall biosynthesis, maintenance of membrane integrity, carbohydrate and energy metabolism, lignin synthesis, and transport of nitrogen and phenolic compounds. Moreover, boron is crucial in pollen tube elongation and fertilization processes. Deficiency in boron disrupts cell division and elongation, slows root growth, reduces flowering and fruit set, and causes necrotic lesions and deformation in tissues, ultimately leading to significant yield and quality losses. On the other hand, excessive boron accumulation can result in toxicity symptoms such as chlorosis, necrosis, and growth inhibition. Therefore, maintaining an optimal boron balance in soil and plant tissues is vital for achieving sustainable crop productivity and quality. Beyond its nutritional significance, boron and boron-containing compounds—particularly **boric acid** and **borates**—have gained considerable attention for their **insecticidal and antimicrobial properties.** These compounds can alter insect feeding behavior, enzyme activities, and physiological balance, ultimately causing mortality. Due to their low toxicity to non-target organisms, biodegradability, and minimal environmental residue, boron-based agents are considered eco-friendly alternatives to synthetic pesticides. Integrating boron-based plant nutrition and pest management strategies may reduce the reliance on conventional chemical insecticides, supporting the development of safer, environmentally responsible, and sustainable agricultural systems. Thus, boron emerges as a promising element that bridges plant nutrition and biological pest control in modern crop production.

Keywords: Boron, boric acid, crop production, pest management, sustainable agriculture.

INTRODUCTION

Boron (B) is one of the seven essential micronutrients required for the optimal growth and development of higher plants. The physiological importance of boron was discovered in 1910, and it was identified in many plant species. In 1923, studies conducted by Warington confirmed that boron is an essential micronutrient for plant growth and development and highlighted its physiological significance (Nielsen, 1988). Although boron was discovered in 1808 by Sir Humphry Davy and Joseph Louis Gay-Lussac, its agricultural significance was not recognized until the early 20th century, when its deficiency was associated with physiological disorders in crops such as sugar beet, alfalfa, and cauliflower (Ahmad et. al., 2006). The effective utilization of boron by plants depends on maintaining adequate and balanced levels of this element in both the soil and plant tissues. Possible ionic imbalances in the soil and within plant tissues may lead to insufficient boron nutrition, resulting in noticeable deficiency symptoms (Deliboran & Savran, 2017).

Boron, which plays a role in carbohydrate metabolism and transport, also has physiological functions in root development as well as in flower and fruit formation (Finck, 1969). It is further reported to be involved in auxin and phenol metabolism, cell membrane and cell wall structure, tissue differentiation, membrane permeability, root elongation, pollen germination and pollen tube growth, sugar transport, leaf elongation and expansion, the regulation of respiration and transpiration, and in enhancing plant resistance not only to viral and fungal diseases but also to insect damage (Deliboran & Savran, 2017). Since boron deficiency primarily affects the growing points of plants, growth slows considerably. Leaves and branches become brittle and easily broken. Under severe deficiency, the growing points die and growth comes to a complete halt. Necrotic spots appear on the leaves, followed by a purplish dark green coloration and downward curling. Moreover, as soluble proteins, chlorophyll, and apical reaction activities decrease within the leaf, stomatal constriction is observed, reducing carbon dioxide movement within the stomata (Dell & Huang, 1997). Deformations in fruits, yellowing at leaf tips, dieback of shoots, fruit drop, abnormalities in peel tissue, and bushy growth due to the death of shoot tips are among the typical symptoms of boron deficiency (Freeman et. al., 1994.; Hartman et. al., 1980.).

Chemically, boron is not found freely in nature; instead, it occurs as B_2O_3 in combination with oxides of other elements (Kemp, 1956). Due to its tendency to form bonds with oxygen, many different boron–oxygen compounds exist. Metal–boron–oxygen compounds are generally referred to as borates. In nature, boron is found in minerals containing sodium, calcium, and magnesium oxides combined with crystal water, known as boron ores or boron salts (Duman, 2003). The simplest boron compounds include boron oxide and boric acid. The calcium-containing form is known as “colemanite,” the calcium–sodium form as “ulexite,” and the sodium-based form as “borax.” Boron is a nonmetal element (atomic number 5), commonly occurring in nature as borates and boric acid. Major natural sources include minerals such as borax ($Na_2B_4O_7•10H_2O$), colemanite ($Ca_2B_6O_{11}•5H_2O$), and ulexite ($NaCaB_5O_9•8H_2O$); many of these are mined in Türkiye, which holds the largest boron reserves in the world. Türkiye possesses 66% of the world's total boron reserves. The country’s known reserves of boron minerals amount to 665,879,243 tons. However, Türkiye ranks second after the United States in boron ore production, with a share of 42.17%. Considering that a comprehensive study determining the precise locations and quantities of Türkiye’s boron reserves has not yet been conducted, it is possible that Türkiye may in fact hold an even larger portion of global reserves. The United States follows Türkiye, holding 13.24% of global reserves. The remaining boron reserves are found in Argentina, Bolivia, Chile, China, Iran, Kazakhstan, Peru, and Russia (bor

5). These reserves, totaling 800 million tons, account for 63% of the world's boron reserves. Türkiye meets 95% of the global raw boron demand with these reserves (Önocak, 1990)

The mobility and availability of boron in soils depend on pH, organic matter, and climatic factors. Many unique properties of boron minerals and their derivatives make them irreplaceable (Göncü, 1982). Borates, which dissolve easily in water, are odorless white crystalline granules or powders. Boron oxide is also a frequently encountered boron compound; notably, boric acid that evaporates from oceans enters the atmosphere and returns to the soil through rain and snow, spreading over wide areas via groundwater and surface water (Demirtaş, 2010). In alkaline soils, boron becomes immobile and inaccessible, whereas in acidic or sandy soils it can leach easily, leading to deficiency conditions (Vera-Maldonado et. al., 2024). A significant portion of plant-available boron in soils is bound to organic matter. Therefore, soils rich in organic matter generally have higher boron levels (Table 1).

Table 1. Agronomic functions and significance of boron in crops.

Agronomic Role	Physiological Function	Implications
Cell wall synthesis	Cross-linking of RG-II pectin chains	Structural stability and growth
Sugar transport	Enhancement of phloem mobility	Improved energy distribution
Reproductive development	Pollen germination and tube growth	Fruit/seed set increase
Nutrient uptake	Interaction with Ca, N, and P	Better nutrient use efficiency

DIFFERENT APPLICATION AREAS OF BORON

Boron minerals can be used in their raw form, but they are generally utilized after being processed into refined boron compounds and end-products (Velioğlu et. al., 1999). Boron is widely used in many industrial sectors, particularly in the glass and detergent industries. In addition, it has an extensive range of applications, from fertilizers and agricultural chemicals to flame-resistant materials, electronics and space technologies, and the agriculture and livestock sectors (Yeşildağ, 2008). For example, it is used in insecticides, ceramics, nuclear reactors, biological growth regulators, photography, plastic and textile industries, fire extinguishers, adhesives, wafer production, cosmetics, electrical herbicides and insulation, and disinfectants (Figure 1). (Doonan & Lower, 1978; Velioğlu et. al., 1999). In the field of health, boron compounds are used in the treatment of osteoporosis and rheumatoid arthritis, in the healing of brain tumors through Boron Neutron Capture Therapy (BNCT), in burn treatments, wound healing, and as antiseptics in lens solutions, ointments, gargles, and eye drops (Kuru & Yarat, 2017).



Figure 1. Different application areas of boron

BORON AND BORON COMPOUNDS IN INSECT PEST MANAGEMENT

Boron-containing compounds have gained considerable scientific attention as promising alternatives in pest management due to their unique chemical structures, environmental compatibility, and broad-spectrum activity against various insect species. Turkey holds the world's largest boron reserves, with an annual production capacity of approximately 3.3 million tons. Elemental boron rarely occurs in pure form in nature; instead, it exists predominantly as borate minerals—oxygen–boron complexes that serve as precursors of a wide array of industrial and agricultural boron compounds (Gore & Schal, 2004). Commercially available boron compounds include borax (sodium tetraborate decahydrate), disodium octaborate tetrahydrate, boric acid, boron oxide, boron carbide, boron nitride, boron trichloride, boron tribromide, and boron trifluoride. Although these substances have diverse industrial applications, the insecticidal properties of boric acid and borate salts have become especially relevant in the search for safer alternatives to synthetic insecticides (Ware, 2000; Sarwar, 2016). Boric acid is one of the oldest inorganic insecticides used in agriculture and public health. It is water-soluble, non-volatile, odorless, and commonly found as a white crystalline powder, characteristics that support its long-term use in household pest control, particularly against cockroaches. Boric acid primarily acts as a stomach poison by interfering with metabolic and digestive processes, ultimately causing insect mortality. Although its precise mode of action is not yet fully elucidated, numerous studies show that boron minerals damage the foregut and midgut epithelium, impair nutrient absorption, and prevent insects from meeting their essential energy requirements (Cochran, 1995; Habes et al., 2006; Büyükgüzel et al., 2013). Another well-supported mechanism involves the abrasive effect of boric acid on the insect cuticle. By adsorbing the waxy epicuticular layer, boric acid accelerates desiccation and increases water loss. In addition to these direct toxic effects, boric acid exhibits sterilizing properties that reduce fecundity and limit population growth, an important advantage in long-term pest suppression programs (Civelek & Dursun, 2013). Compared with conventional chemical insecticides, boron compounds show lower toxicity to humans and domestic animals (Murray, 1998; Weir &

Fisher, 1972). They are inexpensive, highly soluble in water, and notably, despite more than a century of use, there is no evidence of insect resistance to boron-based compounds (Cox, 2004). This characteristic provides a significant advantage in managing pests that have developed resistance to many synthetic chemicals. Boron-containing compounds also play important roles in non-insecticidal applications, including wood preservatives, flame retardants, ceramic and glass manufacturing, and pesticide-free household formulations. They may enter the environment through energy production processes such as coal combustion. In apiculture, boric acid is used in in-hive traps due to its extremely low toxicity to honey bees and classification as a minimally hazardous compound (Atkins, 1987; Harper et al., 2012). Furthermore, boron compounds have demonstrated antifungal potential and are used in pharmaceutical formulations. Despite their extensive use against household pests, research on the effects of boron compounds on stored-product pests remains limited. Korunić et al. (2017) reported that disodium octaborate tetrahydrate effectively controlled *Sitophilus oryzae* (Linnaeus, 1763) without reducing grain bulk density. Additional studies showed that dust and wettable powder formulations of the same compound (F3DOTZ) were highly effective against both *S. oryzae* and *Rhyzopertha dominica* (Korunić & Fields, 2020). A mixture of boric acid and silica (40 g per kg wheat) caused mortality in all developmental stages of *Trogoderma granarium* Everts, 1899 (Falah & Azher, 2020). Laboratory studies further revealed that a combination of 1% boric acid and 10% sucrose reduced populations of *Aedes albopictus* (Skuse) by 98% (Xue & Barnard, 2003). A substantial body of literature documents the physiological and biochemical effects of boric acid on insects. Reported impacts include insecticidal action (Xue & Barnard, 2003; Cruz et al., 2010; Büyükgüzel et al., 2013; Gwokyalya & Altuntaş, 2019), destruction of gut lining and midgut ultrastructure (Cochran, 1995; Habes et al., 2006; Büyükgüzel et al., 2013), reduced fecundity (Kilani-Morakchi et al., 2009), alterations in cuticle composition (Kilani-Morakchi et al., 2005), changes in protein activity and biological fitness (Hyrsl et al., 2007), and induction of oxidative stress (Hyrsl et al., 2008; Büyükgüzel et al., 2013). Recent findings show that boric acid suppresses cellular immunity and induces genotoxic effects in *Galleria mellonella* larvae (Gwokyalya & Altuntaş, 2019), indicating its broad impact on multiple physiological pathways. Collectively, the available scientific evidence highlights boron-containing compounds as highly promising candidates for environmentally friendly pest management. However, the limited number of studies focusing on stored-product pests and the incomplete understanding of the molecular basis of boron toxicity underscore the need for further research. Expanding knowledge on boron compounds may contribute significantly to developing sustainable pest-control strategies that reduce dependence on conventional chemical insecticides.

FUTURE RESEARCH DIRECTIONS

Boron-containing compounds, particularly boric acid and borates, have demonstrated multifaceted potential across agriculture, pest management, and industrial applications. Their unique chemical properties, environmental compatibility, and broad-spectrum activity against diverse insect species distinguish them from conventional synthetic insecticides. The compounds' mode of action encompasses both direct toxic effects—such as disruption of digestive physiology, damage to midgut and foregut tissues, and abrasive effects on the cuticle—and indirect influences, including reduced fecundity, alterations in reproductive processes, and suppression of immune responses. These characteristics collectively contribute to effective pest suppression without the widespread development of resistance, a critical advantage given the growing issue of pesticide resistance in many agricultural and public-health pests.

Beyond their insecticidal activity, boron compounds exhibit low toxicity to mammals and beneficial organisms, including honey bees, making them suitable for integrated pest management and environmentally conscious agricultural practices. Their multifunctional applications—from wood preservation, flame retardancy, and ceramics to pharmaceuticals and fertilizers—underscore the versatility of boron derivatives and highlight their economic and ecological significance. Additionally, Turkey's extensive boron reserves position the country as a global leader in boron production, offering opportunities for both industrial and agricultural utilization of these compounds in cost-effective ways.

Despite the demonstrated promise, significant knowledge gaps remain. Most studies have focused on household and a limited number of stored-product pests, leaving many economically important insect species underexplored. Furthermore, the molecular, physiological, and biochemical mechanisms underlying boron toxicity are not yet fully elucidated. Species-specific responses, environmental interactions, and long-term ecological impacts require comprehensive evaluation to ensure effective and sustainable deployment. Moreover, optimizing formulations, application methods, and concentrations tailored to target pests while minimizing non-target effects is necessary to maximize efficacy.

In conclusion, boron-containing compounds emerge as highly promising tools for sustainable pest management, offering an environmentally friendly and resistance-resilient alternative to conventional insecticides. By integrating these compounds into broader pest-management strategies and continuing interdisciplinary research on their mechanisms, efficacy, and ecological safety, it is possible to achieve effective pest control while minimizing environmental impact. Expanding our understanding and application of boron-based compounds holds considerable potential for enhancing agricultural productivity, protecting stored products, and contributing to more sustainable and responsible pest-management practices globally.

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ASSESSMENT OF AGRICULTURAL WATER USE IN ARID REGIONS: A CASE STUDY OF KONYA - KARAPINAR DISTRICT

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ABSTRACT

Global climate change, unregulated water use, and increasing population pressure have led to a continuous decline in available water resources, particularly in arid and semi-arid regions. This situation adversely affects agricultural production, threatens food security, and causes significant geomorphological changes due to the decline in groundwater levels. The Konya Closed Basin is among the regions most affected by this process, with the increasing occurrence of sinkholes in recent years serving as a striking indicator. Within the basin, the Karapınar district stands out as one of the driest areas in Türkiye. According to 29 years of meteorological data, the average annual precipitation in the district is 279.5 mm. Due to its sparse vegetation and limited forest cover, the region is highly susceptible to wind erosion. These conditions necessitate a more conscious and planned use of water resources in agricultural production. In this study, the irrigation water requirements of the main crops grown in the Karapınar district were determined for the years 2004, 2014, and 2024 (in ten-year intervals). The irrigation water requirements (mm) were calculated using the CropWat 8.0 software developed by the FAO, while data on crop cultivation areas (da) were obtained from the Turkish Statistical Institute (TÜİK). The results indicated that the total irrigation water requirement of crops in the district was 368.5 million m³ in 2004, 426.8 million m³ in 2014, and 689.6 million m³ in 2024. These findings reveal a significant increase in irrigation water demand over the past two decades in Karapınar. This trend poses a serious threat to the sustainability of existing water resources and highlights the necessity of improving water management, enhancing irrigation efficiency, and adopting crop patterns compatible with changing climatic conditions.

Keywords: Crop Water Requirement, CropWat, Karapınar, Irrigation Water Requirement

1. INTRODUCTION

In the context of an increasingly evident global climate change and the growing pressure on water resources, the sustainability of agricultural production -particularly in arid and semi-arid regions- faces a serious threat. As one of the most vulnerable zones of the Konya Closed Basin, understanding the long-term dynamics of agricultural water use in the Karapınar district is essential for identifying the drivers of rising water demand and assessing the depletion rate of existing resources. In this regard, the need for a more efficient, more resilient, and more conscious water management approach for the future has become an inevitable necessity.

In recent years, the accelerating decline in groundwater levels within the Konya Closed Basin has been driven largely by the reliance of agricultural irrigation on groundwater resources. High-water-demand cropping patterns and extensive irrigated areas have pushed groundwater withdrawals to critical levels. Evaluations of measurements obtained from groundwater observation wells across the basin reveal that groundwater levels declined by an average of 1.09 meters per year between 2000 and 2020 (DSİ, 2020; Kalender, 2023). The study conducted by Üstün et al. (2007) further demonstrated that even a 1-meter annual decline in groundwater levels can trigger various environmental and hydrogeological problems in the Konya Closed Basin.

The rapid decline in groundwater levels weakens the load-bearing capacity of karstic voids, leading to roof collapses and triggering sinkhole formation. Carbonic acid generated by the interaction of groundwater with carbon dioxide gradually dissolves carbonate rocks such as limestone, dolomite, and marl; the collapse of voids with weak roofs composed of marl and clayey carbonates results in the development of sinkholes (Orhan et al., 2020). While sinkholes occurred only once or twice per year from the 1920s to the early 2000s, their annual frequency has risen to around forty over the past decade. The cumulative number of sinkholes detected in the Konya Basin to date has reached 2,240 (Çankal & Alkın, 2024). The increasing incidence of sinkholes in Karapınar serves as a strong warning regarding the uncontrolled use of water resources and clearly demonstrates that water must be treated as a strategic asset in all agricultural practices in the region. Accordingly, the aim of this study is to comparatively determine the irrigation water requirements of major agricultural crops grown in the Karapınar district for the years 2004, 2014, and 2024, and thereby reveal the long-term trend in agricultural water demand in the region.

2. MATERIALS AND METHODS

Karapınar, one of the 31 districts of Konya province, is one of Turkey's most important agricultural regions. With a population of approximately 50,000, the district is located 94 km east of the city center (Figure 1). Built on a plain, it is known to be one of the oldest settlements. Known as one of the few tourism areas in Türkiye with its location on the historical Silk Road, its interesting geological structure, its crater lakes with different water characteristics and its uniqueness in the world, Karapınar is also one of the rare regions that can prevent erosion (Anonymous, 2025).



Figure 1. Location of Karapınar district in Konya province

Karapınar, located within the Konya Closed Basin, stands out as one of the regions in Turkey that receives the least rainfall. According to 29 years of observation data, the district's average annual rainfall is 279.5 mm, and due to its sparse vegetation and sparse forest cover, it is extremely vulnerable to wind erosion (T.C. Konya Valiliği, 2025). 22.1% of the areas subject to wind erosion in Turkey occur in and around Karapınar (Bozyiğit and Güngör, 2011). Brown soils predominate in the northeast and southwest of Karapınar, while hydromorphic alluvial soils predominate in the northeast. Soil types such as regosols, black sand dunes, and sierozem soils are also present (Bozyiğit and Güngör, 2011). Total agricultural area information for Karapınar for the years 2004, 2014, and 2024 is provided in Table 1. The size of Karapınar's agricultural land has approximately doubled since 2004, and by 2024, this was due to a significant decrease in total fallow land. Vegetable and grain production areas have increased. Karapınar's share of agricultural land within Konya province has decreased over the years, and this decrease in total fallow land has been a contributing factor.

Table 1. Total agricultural area sizes for Karapınar and Konya provinces (TÜİK, 2025)

Karapınar	Agricultural Area Size (ha)		
	2004	2014	2024
Fruits, Beverages and Spices Crops	1411	203,3	405,1
Fallow	147 485	67 951,4	9500
Vegetable	884	1256	3337,5
Cereals and Other Crop Products	88 497	77 103,8	111 672,3
Total	238 277	146 514,5	124 914,9
Konya Province Total	2 617 944	1 909 248,67	1 884 603,42
Share of Karapınar	% 9,1	% 7,7	% 6,6

The main crops cultivated in Karapınar in 2004, 2014, and 2024 and their production quantities are shown in Table 2. While production of more than half of these crops has increased over the years, barley, watermelon, melon, and grape production has decreased. Based on the crops listed in the table, total production is calculated as 424,122 tons, 1,245,297 tons, and 2,725,336 tons for 2004, 2014, and 2024, respectively. Production has increased by approximately 545% over the past 20 years.

Table 2. Production quantities of main products grown in Karapınar (TÜİK, 2025)

Karapınar	Production Quantity (tons)		
	2004	2014	2024
Wheat	81727	90480	191526
Maize	48765	245802	758777
Barley	66058	29512	35974
Sugar Beet	156729	420020	1101833
Clover	52872	392275	320000
Potato	10513	6749	121123
Carrot	-	13275	135000
Tomato	-	33488	52000
Watermelon	2800	4020	400
Melon	4000	9016	930
Apple	398	172	7710
Grape	260	488	63

Although total agricultural production has increased significantly, the district's population has remained virtually unchanged (Anonymous, 2025). The stagnation of the population and the increase in production have significantly increased the pressure on agricultural water resources in the region and accelerated the rate of increase in irrigation water demand. In parallel, the study demonstrates the changes in irrigation water requirements for major crops grown in the district over time.

CropWat 8.0 and CLIMWAT 2.0 for CROPWAT software developed by FAO were used to calculate irrigation water. Climate data for Karapınar was obtained from CLIMWAT 2.0 for CROPWAT. Crop growing periods and crop growth coefficients (Kc) for some crops were taken from the crop water consumption guide published by TAGEM (2017).

Total irrigation water requirement was calculated in cubic meters (m^3) or tons by multiplying the crop irrigation water requirement (mm) obtained from CropWat by the crop area (da) of the crop. Crop planting areas are compiled from TÜİK (2025). The values obtained represent net irrigation water requirements, and irrigation efficiency is not considered. Crop irrigation water requirement (mm) data were assumed to be the same for the same crop in three years (2004, 2014, and 2024).

3. RESEARCH RESULTS AND DISCUSSION

This section provides a comparative assessment of the planting areas, net irrigation water requirements, and changes over time for the main agricultural crops cultivated in the Karapınar district in 2004, 2014, and 2024. The data obtained reveal the impact of the expansion trend in agricultural production on water resources and, in particular, how changes in crop patterns affect irrigation water demand. When the calculated crop water consumption values for three different years are considered, along with the differences in total planting areas and the decline in groundwater levels, it is clear that agricultural water use in Karapınar is becoming increasingly critical.

The planting areas and net irrigation water requirements of the main crops cultivated in the Karapınar district in 2004 are given in Table 3. Total planting area was 892,790 m³, and total irrigation water requirement was 368,499,147 m³. The average irrigation water requirement per decare was 412.8 mm.

Table 3. Planting areas and net irrigation water requirements of crops in 2004

2004			
Crop	Planting Area (da)*	Net Irrigation Water Requirements	
		(mm)	(m^3)
Wheat	377 330	397,5	149 988 675
Barley	275 070	288,1	79 247 667
Rye	86 880	371,8	32 301 984
Maize	52 000	708,0	36 816 000
Sugar Beet	41 550	838,3	34 831 365
Clover	20 210	853,3	17 245 193
Oat	10 060	316,3	3 181 978
Chickpeas	8 000	502,5	4 020 000
Cumin	9 500	321,8	3 057 100
Melon	4 000	571,1	2 284 400
Potato	3 010	655,9	1 974 259
Grape	1 400	582,2	815 080
Apple	1 240	797,3	988 652
Apricot	1 040	807,6	839 904
Watermelon	700	588,1	411 670
Beans	500	581,6	290 800
Pepper	300	681,4	204 420
Total	892 790	412,8	368 499 147

* TÜİK, 2025

The planting areas and net irrigation water requirements of the main crops cultivated in 2014 are given in Table 4. Total planting area was 789,062 da, and total irrigation water requirement was 426,801,582 m^3. The average irrigation water requirement per decare was 540.9 mm.

Table 4. Planting areas and net irrigation water requirements of crops in 2014

2014			
Crop	Planting Area (da)*	Net Irrigation Water Requirements	
		(mm)	(m^3)
Wheat	257 996	397,5	102 553 410
Maize	159 871	708,0	113 188 668
Barley	151 493	288,1	43 645 133,3
Sunflower	67 866	666,5	45 232 689
Clover	67 141	853,3	57 291 415,3
Sugar Beet	61 811	838,3	51 816 161,3
Tomato	5 600	698,4	3 911 040
Rye	4 581	371,8	1 703 215,8
Carrot	2 655	650,6	1 727 343
Melon	2 800	571,1	1 599 080
Chickpeas	2 500	502,5	1 256 250
Potato	1 500	655,9	983 850
Grape	1 400	582,2	815 080
Watermelon	1 005	588,1	591 040,5
Oat	388	316,3	122 724,4
Apple	289	797,3	230 419,7
Apricot	166	807,6	134 061,6
Total	789 062	540,9	426 801 582

The planting areas and net irrigation water requirements of the main crops cultivated for 2024 are given in Table 5. Total planting area was 1,210,665 acres, and total irrigation water requirement was 689,646,348 m^3. The average irrigation water requirement per decare was 569.6 mm.

Table 5. Planting areas and net irrigation water requirements of crops in 2024

2024			
Crop	Planting Area (da)*	Net Irrigation Water Requirements	
		(mm)	(m^3)
Wheat	400 000	397,5	159 000 000
Maize	342 100	708,0	242 206 800
Barley	125 000	288,1	36 012 500
Sunflower	42 000	666,5	27 993 000
Sugar Beet	120 224	838,3	100 783 779,2
Clover	80 000	853,3	68 264 000
Vetch	33 700	347,1	11 697 270
Tomato	5 200	698,4	3 631 680
Rye	3 200	371,8	1 189 760
Carrot	27 000	650,6	17 566 200
Melon	310	571,1	177 041
Chickpeas	700	502,5	351 750
Potato	27 000	655,9	17 709 300
Lettuce	260	228,2	59 332
Grape	250	582,2	145 550
Almond	716	734,2	525 687,2
Watermelon	80	588,1	47 048
Oat	100	316,3	31 630
Apple	2 665	797,3	2 124 804,5
Apricot	160	807,6	129 216
Total	1 210 665	569,6	689 646 348

The total net irrigation water requirement for crops grown in the Karapınar district was calculated as 368.5 million m^3 in 2004, 426.8 million m^3 in 2014, and 689.6 million m^3 in 2024. Accordingly, irrigation water requirement has increased 1.87-fold over a 20-year period. In addition to the increase in total planting area, the decrease in the planting area of some crops with relatively low water requirements (barley, rye, oats, cumin) and the increase in the planting area of some crops with high water requirements (maize, sugar beet, clover) directly contribute to this situation.

Decreased precipitation, particularly due to global warming, has also led to a decline in groundwater levels in the region. Considering the level changes over the years in the five

observation wells located in Karapınar, significant level drops are evident (DSİ, 2020). Information on the observation wells is provided in Table 6.

Table 6. Level changes in the level observation wells in Karapınar (DSİ, 2020)

District	Location	Water Levels (m) and Years	Level Change (m)
Karapınar	Akören	32,71 - 43,35 (2015-2020)	-10,64
	Kesmez	44,00 - 52,66 (2015-2020)	-8,66
	Cumhuriyet	54,09 - 57,67 (2015-2020)	-3,58
	Akçayazı	47,96 - 61,47 (2015-2020)	-13,51
	Gülfet Yayla	27,63 - 65,92 (2000-2020)	-38,29

Studies in the literature conducted in arid and semiarid regions demonstrate the critical importance of irrigation scheduling for the sustainable management of water resources. Numerous studies have analyzed the water requirements of crops in different climates using CropWat software, emphasizing that water deficits increase during periods of insufficient rainfall, making accurate timing and effective irrigation programs essential. Studies in water-scarce regions such as Burkina Faso, Rwanda, India, Tunisia, and Botswana have demonstrated that CropWat significantly contributes to accurate crop water requirement calculations, better monitoring of soil water balance, and more efficient water use (Some et al., 2006; Rose et al., 2019; Herrero Batalla et al., 2014; Mal and Sen, 2025; Haj-Amor, 2020; Moseki, 2025). Appropriate irrigation timing for the growing season, particularly in semiarid regions, has been shown to have a decisive impact on crop yield. These assessments are consistent with the findings obtained in Karapınar. The expansion of the cultivation area of high-water-consuming crops in the district has led to a rapid increase in total irrigation needs; at the same time, the significant decline in groundwater levels has demonstrated that irrigation management now requires more precise planning. Therefore, in Karapınar, as in other arid regions, supporting irrigation programs with scientifically based software is a critical requirement for efficient water use and sustainable production.

4. CONCLUSION AND RECOMMENDATIONS

This study comparatively analyzed the cultivation areas, production quantities, and net irrigation water requirements of the main agricultural products grown in the Karapınar district for the years 2004, 2014, and 2024. The findings indicate that Karapınar is highly vulnerable to water scarcity due to its arid and semi-arid climate, and that agricultural water demand has increased significantly over the last 20 years.

When evaluated in terms of crop pattern, planting areas, and production quantities, total production increased from 424,000 tons in 2004 to 2.7 million tons in 2024 (a 545% increase), demonstrating a significant expansion in agricultural activities. Conversely, the district's population remained virtually constant over the same period, indicating that the pressure on water resources caused by increased production stems from agricultural production rather than human consumption. Furthermore, the shift in crop pattern is a significant driver of the increase in water demand. While the area under cultivation for low-water-demand crops like barley, oats, rye, and cumin has decreased, the area under cultivation for high-water-demand crops like maize, sugar beet, and clover has expanded significantly. This change negatively impacts the sustainability of agricultural water use in the region.

Analyses of irrigation water requirements clearly demonstrate this trend. Total net irrigation water requirements, which were 368.5 million m³ in 2004, reached 426.8 million m³ in 2014, and 689.6 million m³ in 2024. This represents a 1.87-fold increase in water demand over the past 20 years. An examination of the tables reveals that maize, sugar beet, clover and wheat, in particular, account for a significant portion of total irrigation water requirements, both in terms of crop area and total water consumption. The fact that maize's irrigation water needs exceeded 242 million m³ in 2024 indicates that the region's water budget has reached a critical point.

Meanwhile, levels measured in five groundwater observation wells in Karapınar indicate that this pressure on the water budget is directly reflected in groundwater levels. The average drop in groundwater levels between 2000 and 2020 was calculated as -1.8 m/year; drops exceeding 8-13 meters were recorded over a five-year period in locations such as Akçayazı, Akören, and Kesmez. The most striking drop, at -38.29 meters over 20 years, was observed in the Gülfet Yayla well. This rapid decline in groundwater levels demonstrates that agricultural activities are currently unsustainable and increases geomorphological risks such as sinkhole formations.

In light of these findings, several recommendations can be developed. The uncontrolled growth of crops such as maize, clover and sugar beet, which require high water consumption, is rapidly depleting the basin's water budget. A transition to a water-friendly cropping pattern has become a strategic necessity for the region. A return to relatively low-water-demand crops such as barley, oats, rye, and cumin should be encouraged. Traditional irrigation methods, which persist in Karapınar, significantly increase water losses. Supporting the transition to systems such as drip and sprinkler irrigation will increase water use efficiency. To make these technologies economically accessible, support and subsidy mechanisms should be established for farmers. Illegal wells should be identified, water withdrawal permits should be reissued according to the current water budget, and wells should be integrated with monitoring systems. If the decline in groundwater levels continues, agricultural production will be at significant risk, and sinkhole formation will become more widespread. Alternative methods such as rainwater harvesting, small storage structures, surface runoff collection, and the use of reclaimed water for agricultural irrigation will reduce groundwater dependency. Karapınar's sand dunes, regosols, and brown soils have low water holding capacity and are susceptible to erosion. Therefore, organic matter applications (farm manure, compost), mulching techniques, and proper planning of soil tillage timing will improve the plant-water relationship and support production with less irrigation water. Continuous training for farmers on efficient water use, soil-plant-water relationships, irrigation scheduling, and adaptation to climate change should be provided; the field application of technological innovations should be supported.

The Karapınar district is one of Turkey's most vulnerable agricultural production areas due to its arid climate, low rainfall, the threat of wind erosion, and rapidly declining groundwater levels. The study's findings clearly demonstrate that if current water use trends continue, the region's water sustainability is at serious risk. Therefore, a holistic approach to water management should be adopted; a water-efficiency-based production approach is essential for the region's future.

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NUMERICAL ANALYSIS OF INTERNAL FLOW CHARACTERISTICS IN HOLLOW CONE NOZZLE PLATES USED IN PESTICIDE APPLICATIONS

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ABSTRACT

The uniform distribution of pesticides to the target with minimal loss is directly related to the internal flow uniformity of the spray nozzles. The internal structure of standard spray nozzles, by design, contains sudden cross-sectional constrictions. The aforementioned geometric changes result in the disruption of the velocity profile within the flow channel. This, in turn, gives rise to the formation of sharp velocity gradients, an increase in turbulent kinetic energy, and sudden pressure drops in the constriction regions. It is imperative to note that these flow irregularities have the potential to exert a detrimental influence on the quality of pulverization and the homogeneity of the spray distribution. This phenomenon can be attributed to the propensity of such irregularities to give rise to the development of vortex structures and to the weakening of jet stability. Consequently, it is imperative to quantitatively ascertain the effect of the internal geometry of spray nozzles on flow characteristics for the purpose of optimising design. In this study, the behaviour of the flow in the nozzle body channel was analysed in detail at three different pressure levels (2, 3 and 4 bar) by means of computational fluid dynamics (CFD) methods. Experimental flow measurements were conducted in order to establish boundary conditions. The theoretical velocity values that were calculated were then compared with the simulation results. In the context of HAD analyses, the velocity, pressure, and turbulent kinetic energy distributions within the nozzle body were evaluated at each pressure level. This facilitated the identification of discrepancies in flow characteristics. The findings demonstrated that analyses conducted at an operating pressure of 3 bar exhibited the strongest concordance with the experimental data. Furthermore, it was revealed that selecting the appropriate operating pressure could create a more stable, symmetrical, and energy-efficient profile for the flow inside the nozzle. These findings provide a scientific basis for future optimisation studies aimed at eliminating flow irregularities caused by internal geometry and improving atomisation performance in spray nozzle design.

Keywords: Spray nozzle, computational fluid dynamics (CFD), velocity profile, pressure drop, turbulent kinetic energy

INTRODUCTION

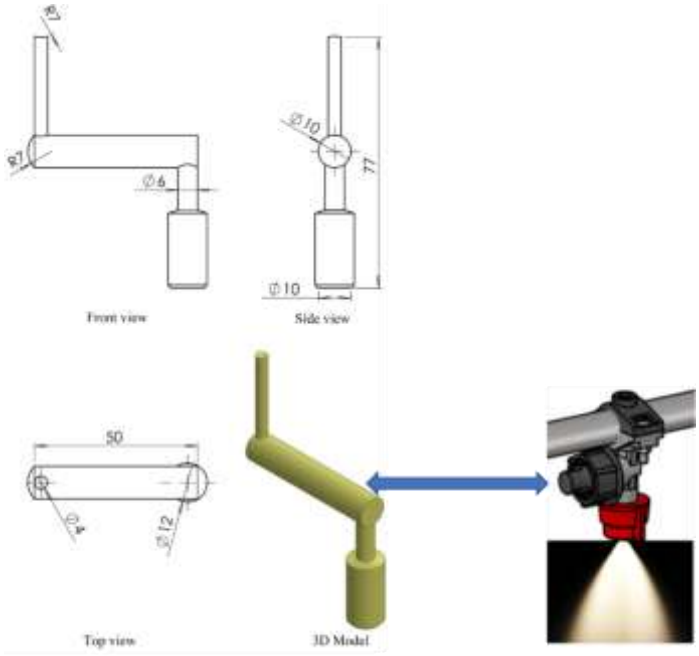
The uniform distribution of pesticides to the target is directly related to the internal flow uniformity of the spray nozzles. In this context, the design characteristics and operating parameters of sprayers directly influence the effectiveness of agricultural pest control (Çomaklı, 2017). The liquid pesticide contained within the sprayer tank is pressurised prior to being discharged into the atmosphere through the function of the spray nozzles. It should be noted that a certain level of pressure loss occurs during this process, due to friction along the inner surface of the hose, particularly at the elbow sections where the flow direction changes. In hydraulic pipe systems that are designed for the direction and transportation of fluids, elbow joints that facilitate alterations in flow direction and reducers that enable diameter transitions between pipes are among the most frequently utilised connection components (Andrew, 2011). In the domain of fluid transfer systems, elbow components assume a pivotal role in facilitating optimal flow conditions. This is attributable to their direct impact on the velocity and pressure distributions of the fluid, thereby ensuring efficient redirection of flow (Danışmaz, 2023). In hydraulic hose and pipe systems, pressure losses occur to a certain extent due to the resistance generated during fluid flow. In particular, examination of the flow behaviour in elbow regions is of critical importance for understanding and improving overall system performance (Korkmaz and Tıkız, 2023). Elbow components, where directional changes occur within sprayer pressure hose systems, play a pivotal role in overall system performance by directly influencing the flow's velocity and pressure parameters. The turbulence, vortex formation, and pressure losses that arise in such connection components have a significant impact on both flow efficiency and distribution accuracy. It is imperative to comprehend the distribution of flow within the flow-directing elbows, otherwise referred to as nozzle heads, through which pressurised fluid passes prior to reaching the spray nozzle. This understanding is of paramount importance for the design and optimisation of hoses and connection components in the sprayer pressure line. The time-consuming and costly nature of experimental studies increases the importance of numerical analysis methods, which can provide fast and reliable results. In a study conducted by Özkan (2011), the flow characteristics of the existing model were examined using the computational fluid dynamics software FLUENT in order to design a new 90° elbow that could provide lower pressure loss compared to conventional connection components. In their study, Bostancı and Ünalan (2012) conducted a numerical investigation into the flow of incompressible turbulence in a square-section elbow with a 90° bend. In the course of the study, the researchers compared various turbulence models with the experimental results, concluding that the RNG k-ε model was the most suitable for square-section elbows. Danışmaz (2023) investigated the flow behaviour of water and water-based Al_2O_3 nanofluid in an elbowed pipe under constant heat flux surface boundary conditions and at low Reynolds numbers using computational fluid dynamics. In their study, Korkmaz and Tıkız (2023) examined various bend diameters and bending defects, which are frequently encountered during pipe manufacturing, in order to detect deformation errors. They also determined the associated pressure losses using the k-ε turbulence model. In this context, the design and modelling of components within flow lines can be carried out in a shorter time and at a lower cost by using simulation techniques. This enables effective and economical solutions to flow-related problems. Computational Fluid Dynamics (CFD) is an approach that enables the sequential solution of flow problems with complex geometries, encountered in real-life applications, through the use of differential equations expressed by numerical methods. This is particularly useful in cases where analytical solutions are not feasible (Chung, 2002).

In this study, the influence of elbow geometries - located within the pressure hose systems of sprayers widely used in agricultural applications - on overall system performance was examined

in detail using the CFD method. In particular, the velocity gradients, pressure drops, and turbulence structures that occur in elbow regions were analysed comprehensively. These regions are of particular interest as they are where the fluid is forced to change direction and constitute the main source of energy losses. The numerical analyses were conducted using ANSYS Fluent, and the three-dimensional flow domain of the nozzle head - representing the critical region immediately preceding the spraying process - was modelled in great detail. An investigation was conducted on a cone-jet nozzle with a 2.4 mm orifice diameter, a model that has been widely adopted within the industry. The model was defined through the application of boundary conditions that align with the operational parameters across a range of three distinct pressures. Following the execution of the simulations, a comparative analysis was conducted on variations in key flow parameters. These parameters included, but were not limited to, velocity distributions, static and dynamic pressure changes, and turbulence kinetic energy distributions. The findings, both quantitative and qualitative, demonstrate the pivotal role of elbow geometry in hydraulic system efficiency and spray quality. Furthermore, they identify the critical parameters that should be considered during the design of optimised sprayer systems in terms of energy efficiency and wear resistance.

MATERIALS AND METHODS

In the present study, an analysis was conducted of the flow domain within a spray nozzle head manufactured from polyamide material, which features a 90° bend. The nozzle head comprises two distinct sections, as illustrated in Figure 1a and 1b: a 4 mm fluid inlet diameter and a 10 mm outlet surface diameter situated immediately upstream of the cone-jet nozzle. In the present study, the inlet velocity and pressure values of the 2.4 mm orifice spray nozzle utilised in the research conducted by Çomaklı and Sayıncı (2022), entitled “Determination of Orifice Flow Velocity in a Cone-Jet Nozzle by Experimental and Computational Fluid Dynamics (CFD) Methods”, were adopted as the target outlet values.



(a) (b)

Figure 1. (a) Technical drawings of the spray nozzle head flow domain, (b) Flow within the spray nozzle head

Theoretical calculations were performed to determine the inlet velocity values for three distinct operating pressures (2, 3, and 4 bar) utilising the general volumetric flow rate equation. (Equation (1)). The preceding study determined that the theoretically calculated inlet velocities were consistent with the experimental data with an accuracy of 96%. In the context of this study, the inlet velocity values were considered as a reference point, with the outlet velocities of the spray nozzle head being targeted and examined accordingly. The three-dimensional flow domain of the spray nozzle head was modelled in SolidWorks 2023, and subsequently analysed using the CFD method within the ANSYS 2021 R1 Workbench environment. The outlet velocities obtained were then compared with the inlet velocity values from the previous study, and a detailed evaluation was conducted.

The general equation for flow rate (volumetric flow rate) is as follows:

$$Q = A \cdot V \tag{1}$$

Where, Q is the volumetric flow rate ($m^3\ s^{-1}$), A is the cross-sectional area (m^2), and V is the fluid velocity ($m\ s^{-1}$).

In the experimental calculations of the orifice outlet velocity, water was selected as an incompressible and constant-density fluid, and these properties were defined in the ANSYS Fluent model. The inlet diameter of the spray nozzle head was measured to be 4 mm, and it was used in the determination of the Reynolds numbers based on the calculated flow velocities. In practice, the pressurised pesticide solution contained within the sprayer tank is delivered to the spray nozzle head through a 13 mm diameter pressure line. The flow from the pressure line to the nozzle head is directed through 90° turns, and the flow in this inlet region generally occurs in a turbulent regime. The Reynolds number is defined as the ratio of inertial forces to viscous forces and is utilised to ascertain the flow regime. For flow in circular pipes, the Reynolds number was calculated using the following equation (2). In order to ascertain whether the flow in the spray nozzle head was laminar or turbulent, the Reynolds number was evaluated using the following equation.

Reynolds number equation:

$$Re_D = \frac{\text{Inertial forces}}{\text{Viscous forces}} = \frac{\rho \cdot V \cdot D}{\mu} \tag{2}$$

Where Re_D: Reynolds number, ρ: the fluid density (998 $kg\ m^{-3}$), V: the fluid velocity ($m\ s^{-1}$), D: the inlet diameter (m), μ: the dynamic viscosity (0.001 Pa.s)

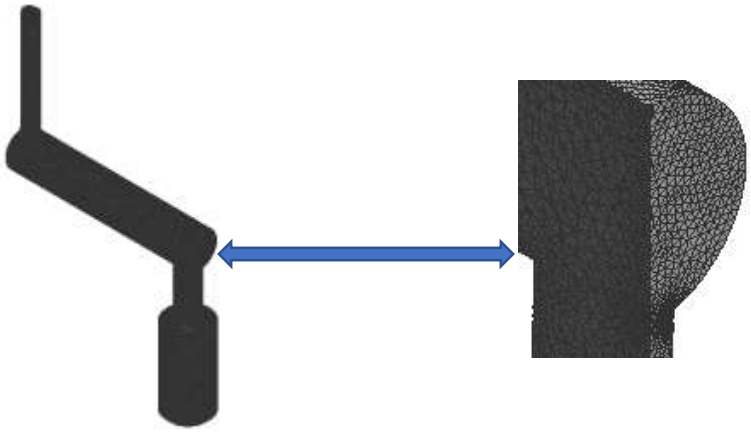
The inlet velocities calculated for three different operating pressures (2, 3, and 4 bar), along with the corresponding Reynolds numbers determined based on these velocities, are presented in Table 1.

Table 1. Calculated velocity values and Reynolds numbers for different operating pressures

Operating pressure (bar)	Inlet velocity of the spray nozzle head ($m\ s^{-1}$)	Reynolds Number
2	2.610	10400
3	3.169	12620
4	3.710	14790

It is acknowledged that flow occurs in a turbulent regime when the Reynolds number is 4000 or higher. According to the data presented in Table 1, the lowest Reynolds number measured at the inlet of the spray nozzle head was determined to be 10.400, and the flow was therefore considered turbulent.

Kibar et al. (2021) conducted a study on the pressure drop in banjo elbows, which are extensively employed in high-pressure applications. The study utilised the standard k–ε turbulence model. Çavdar et al. (2020) demonstrated a preference for the standard k–ε turbulence model when examining the pressure and velocity variations occurring in the internal flows of solenoid valves utilised in the domain of pneumatic control. In a study conducted by Shabani et al. (2019), the standard k–ε turbulence model was employed to simulate the pressure distribution and losses caused by turbulent flows in a circular pipe elbow with and without guide vanes. In view of the findings of the literature review and the converging-diverging diameter structure of the spray nozzle head, it was determined that the standard k-ε turbulence model would be utilised as the turbulence model in this study. As demonstrated in Figure 2, the numerical solution mesh of the spray nozzle head was presented. In order to achieve a higher level of accuracy in the critical transition regions of the flow domain, a denser mesh structure was generated by activating the 'capture' and 'proximity' options. In order to ensure mesh independence of the solution, mesh structures with three different element sizes were generated, and the mesh parameters are presented in Table 2. The numerical analyses were performed using ANSYS Fluent, with the standard k–ε turbulence model being employed and adaptive meshing techniques being applied to enhance the accuracy of the solution.



(a) (b)

Figure 2. (a) Flow domain mesh structure, (b) Detailed sectional mesh structure

In the context of the flow domain of the spray nozzle head, three distinct mesh structures were generated. Of these, the mesh with an element size of 0.4 mm was selected on the basis that it predicted the experimental velocity values with high accuracy and enabled rapid solution convergence. As illustrated in Table 2, the number of elements determined through a trial method is presented, with said determination based on the selected element sizes.

Table 2. Number of cells determined to achieve the closest match to the theoretical velocity value

Element size (mm)	Number of elements	Number of adaptive elements	Theoretical velocity (m s^{-1})	CFD velocity (m s^{-1})	Accuracy (%)
0.3	940737	1045653	0.510	0.531	96
0.4	511784	571778	0.510	0.512	99
0.5	325260	368079	0.510	0.504	98

A series of numerical analyses were conducted on the flow domain of the spray nozzle head. The results obtained after 5000 iterations used an adaptive mesh resolution of 0.4 mm. These analyses were performed under three distinct boundary conditions, representing different operating pressures. The experimental and simulation velocity values obtained at the conclusion of each 1000-iteration period under an operating pressure of three bar are presented in Table 3. Polyamide, a material frequently preferred in engineering applications, was selected for the construction of the spray nozzle head.

Table 3. Outlet values obtained after each 1000 iterations using the number of cells determined to achieve the closest match to the theoretical velocity value

Iteration number	Inlet (m s^{-1})	Outlet (m s^{-1})	Theoretical (m s^{-1})	Accuracy (%)
1000	3.169	0.512	0.510	99.6
2000	3.169	0.513	0.510	99.4
3000	3.169	0.514	0.510	99.2
4000	3.169	0.512	0.510	99.6
5000	3.169	0.512	0.510	99.6

Governing Equations

The CFD simulations conducted in this study were based on the fundamental conservation equations governing fluid behaviour (mass and momentum). In accordance with the definition of the computational domain as single-phase, comprising solely water flow, the equations were evaluated under the assumption of incompressible flow. To ascertain the internal flow characteristics within the spray chamber, the steady-state form of these conservation equations was solved.

Conservation of mass (Continuity equation):

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{3}$$

Here, ρ represents the fluid density (kg m^{-3}), and u, v, w are the velocity components in the x, y, and z directions, respectively (m s^{-1}).

Conservation of momentum (Navier-stokes equations):

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\rho g_x+\mu\vec{\nabla}^2 u \quad (4)$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial y}+\rho g_y+\mu\vec{\nabla}^2 v \quad (5)$$

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial z}+\rho g_z+\mu\vec{\nabla}^2 w \quad (6)$$

In this context, the symbol p denotes the static pressure (Pa), μ is the dynamic viscosity (Pa·s), and g_x, g_y, g_z are the components of gravitational acceleration (m s^{-2}).

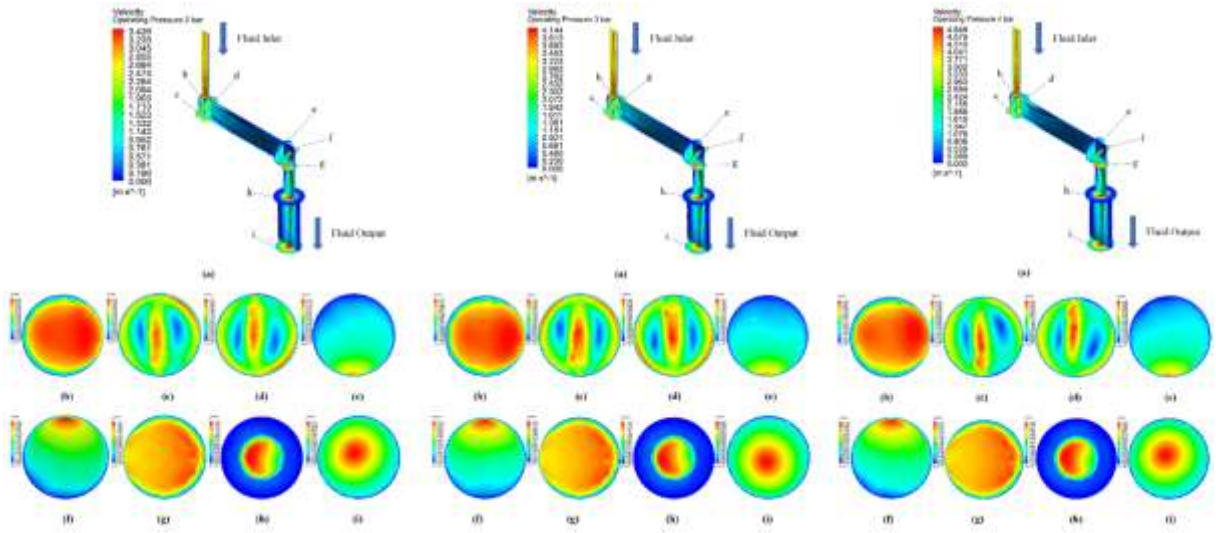
RESULTS AND DISCUSSION

In this study, the theoretical and computational fluid dynamics velocity results for the nozzle head at three different operating pressures are presented in Table 4. The research findings indicate that the theoretical outlet velocities were verified with an accuracy of over 99% at all three pressure levels. The computational fluid dynamics results for the spray nozzle head exhibited the highest agreement with the experimental results at an operating pressure of 3 bar. It was observed that the outlet velocity of the nozzle head increased with the rise in operating pressure.

Table 4. Calculated velocity values and CFD results for different operating pressures

Operating pressure (bar)	Inlet velocity (m s^{-1})	Outlet velocity (m s^{-1})	Theoretical outlet velocity (m s^{-1})	Accuracy (%)
2	2.610	0.423	0.420	99.2
3	3.169	0,512	0,510	99.6
4	3.710	0.601	0.597	99.3

The distributions of velocity, pressure, and turbulence kinetic energy obtained at the operating pressures were presented in detail through visualisations on selected cross-sectional planes. These planes had been chosen to reveal the effects of geometric features such as the 90° turning regions, diameter transitions, and the cone-jet nozzle inlet section within the nozzle head. In the three analyses under consideration, image (a) is representative of the general flow field, whilst images (b)-(i) illustrate the distributions on various cross-sectional planes selected along the flow path. Figure 3 presents the velocity distributions obtained along the flow path within the nozzle-head system under three different operating pressures.

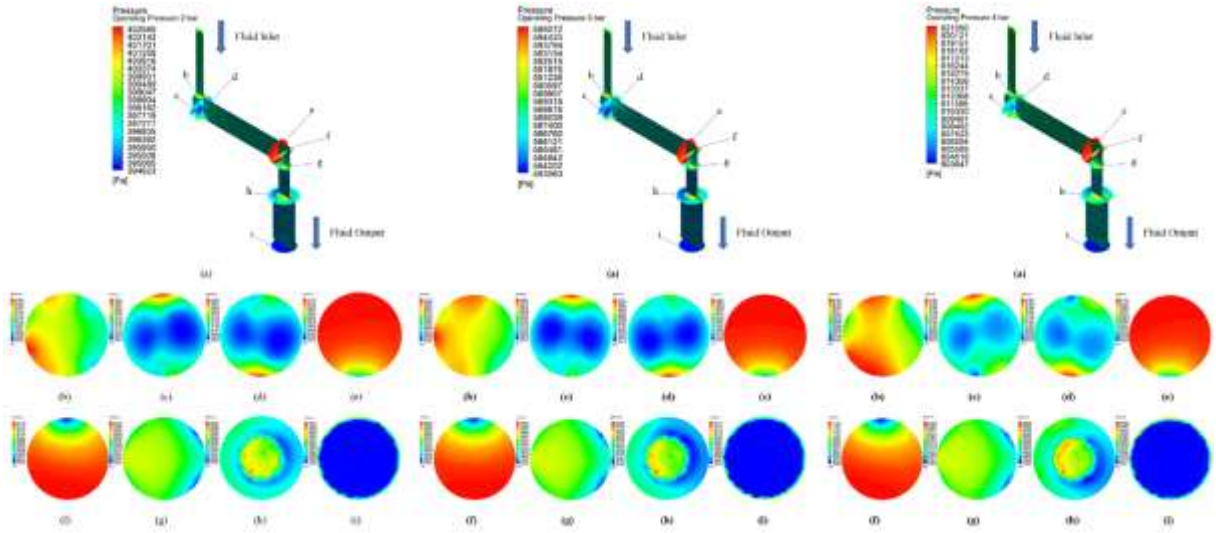


(a) (b) (c)

Figure 3. Velocity distributions at (a) 2 bar, (b) 3 bar, and (c) 4 bar operating pressures

In the configuration of the pipe (b), the flow velocity within the 4 mm diameter pipe section in the vicinity of the inlet achieves its maximum value within the flow domain for all operational pressures. The velocity distributions at all pressure levels exhibit a concentration at the centre, a gradual decrease towards the walls, and an asymmetric pattern. In planes (c) and (d), where the diameter of the spray nozzle head abruptly increases from 4 mm to 10 mm and the flow direction is altered by 90°, the velocity is observed to decrease at all pressure levels due to the consequences of sudden expansion and rotation, resulting in the formation of an asymmetric pattern from the centre towards the outer regions. This behaviour is indicative of the influence of turbulent structures and secondary flows generated by the change in flow direction and the geometric expansion. As the pressure increases, the two-lobed velocity structures induced by the turning motion become more pronounced. In plane (e), where the diameter remains constant at 10 mm, the velocity decreases across the flow region at all pressure levels due to the preceding expansion. In plane (f), although the diameter remains constant, the centrifugal forces generated by the elbow geometry distort the velocity distribution at all pressure levels, causing the flow to shift towards one side. As the pressure increases, the velocity asymmetry becomes more pronounced due to the intensified centrifugal effects. In plane (g), the sudden reduction of the cross-sectional diameter to 6 mm increases the velocity, resulting in a more focused and homogeneous flow profile. In the plane (h), as the diameter expands to 12 mm, the velocity remains relatively high at the centre while decreasing markedly towards the walls. The occurrence of the highest flow velocity at the 4-bar operating pressure can be interpreted as an indication that the acceleration of the flow is not adversely affected by the diameter variations. In the initial configuration (i), the diameter undergoes a further reduction to 10 mm, thereby inducing a concentration of the velocity distribution at the centre and the formation of a more uniform profile. It is evident that the velocity values exhibit an overall increase across all cross-sections as the operating pressure rises. It has been demonstrated that the geometric effects engender equivalent flow characteristics across the entire range of pressure levels. The 4-bar operating pressure is defined as the condition in which the flow attains its maximum velocities and demonstrates the most intense turbulence intensity.

As illustrated in Figure 4, the pressure distributions obtained along the flow path are presented for the system containing a spray nozzle head with a 90° change in flow direction under three different operating pressures.

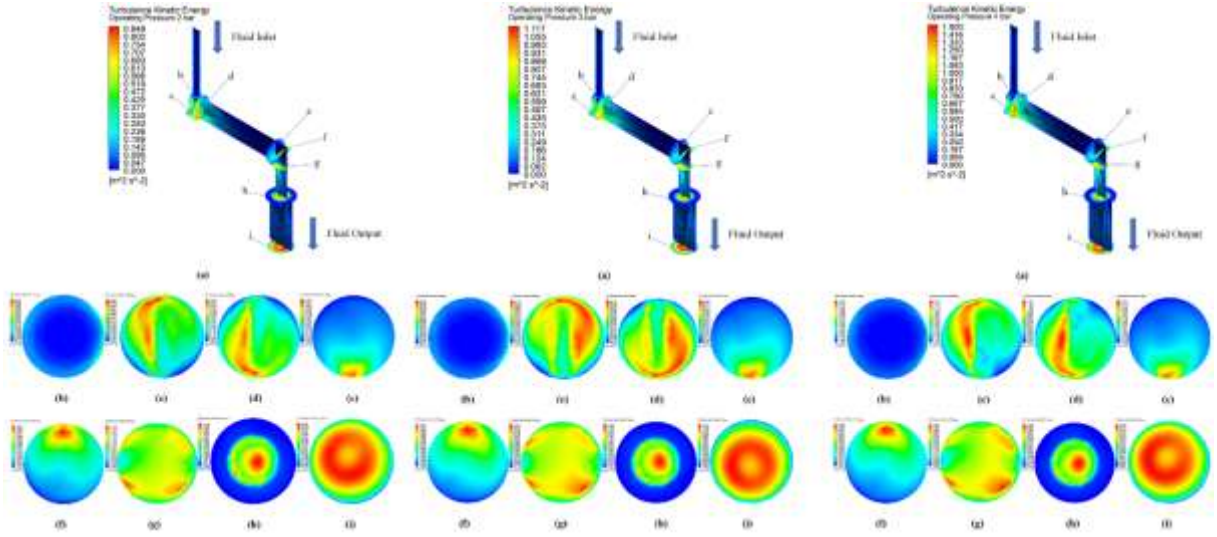


(a) (b) (c)

Figure 4. Pressure distributions at (a) 2 bar, (b) 3 bar, and (c) 4 bar operating pressures

In the (b) plane, the static pressure reaches its maximum levels in the sections in close proximity to the inlet region. As the operating pressure increases, a consistent rise in pressure is observed throughout the entire inlet region. The pressure distributions at the inlet cross-section exhibit higher values at the centre, decreasing progressively towards the walls. It is evident that planes (c) and (d) represent the critical regions where the flow undergoes a sudden expansion from 4 mm to 10 mm and a 90° change in direction. At all pressure levels, the sudden expansion causes a drop in pressure, and the change in flow direction makes the pressure distribution asymmetric. As the pressure increases, high-pressure pockets become more pronounced along the side walls, whilst low-pressure cores emerge in the regions that are distant from the centre. Subsequent to the sudden expansion, the pressure profile in the 10 mm constant-diameter segment begins to re-establish equilibrium in the plane (e). As the pressure is increased from 2 bar to 3 and 4 bar, the pressure gradient increases concomitantly. Plane (f) demonstrates that the geometry of the elbow causes a shift in the pressure distribution, resulting in an evident asymmetry across the section. As the operating pressure increases, the centrifugal effect causes the pressure to rise along the outer curvature and decrease along the inner curvature. In plane (g), the sudden reduction of the cross-sectional diameter from 10 mm to 6 mm causes an abrupt increase in pressure within the section. It has been demonstrated that, at the 4-bar operating pressure, this region exhibits the most pronounced pressure concentration. The reduction in cross-sectional area causes the fluid to accelerate, leading to the accumulation of pressure concentration at the centre. In plane (h), the augmentation of the diameter to 12 mm engenders a diminution in pressure distribution, with reduced values at the centre and elevated values in proximity to the walls. At elevated pressure levels, turbulence cores induced by the expansion become distinctly visible. In plane (i), the narrowing of the geometry back to 10 mm consolidates the pressure distribution at the centre. It has been demonstrated that, under all pressure levels, pressure values decrease in proportion to the increase in flow velocity towards the outlet surface. Consequently, as pressure increases, pressure levels rise in all regions; however, the geometric effects continue to produce the same flow patterns. The regions of directional change, expansion, and contraction generate significant asymmetry and turbulence structures in the pressure distributions. The geometry of the nozzle head generates pressure peak and trough regions along the flow path, thereby significantly altering the overall flow balance.

As illustrated in Figure 5, the distributions of turbulence kinetic energy (TKE) of the spray nozzle head at three distinct operating pressures are presented in detail across the (b)-(i) planes.



(a) (b) (c)

Figure 5. Turbulent kinetic energy distributions at operating pressures of (a) 2 bar, (b) 3 bar, and (c) 4 bar.

In the configuration delineated by plane (b), the turbulence kinetic energy remains low at all pressure levels. Even as the operating pressure increases, turbulence generation remains limited because the flow does not encounter any major geometric changes. In planes (c) and (d), flow separation and the formation of vortex structures are precipitated by the sudden expansion and change in flow direction. Turbulence kinetic energy manifests an asymmetric and sharp increase from the centre towards the outer regions. As the operating pressure increases, the dual-core turbulence structures become more pronounced. In the case of plane (e), within the straight-flow region characterised by a constant diameter of 10 mm, a significant decrease in turbulence kinetic energy has been observed across all pressure levels. In plane (f), the presence of the elbow geometry leads to the deflection of the flow towards the outer curvature, thereby resulting in the formation of high turbulence kinetic energy. As the operating pressure increases, the centrifugal effects become stronger, and the asymmetry in turbulence kinetic energy becomes more pronounced. In the configuration represented by the letter g, the abrupt reduction in the cross-sectional area to 6 mm leads to an increase in flow velocity, consequently resulting in a substantial rise in turbulence kinetic energy. The 4-bar pressure level resulted in the most significant turbulence intensification. In the case of plane (h), the sudden expansion of the cross-section to a diameter of 12 mm results in a significant reduction in turbulence kinetic energy. In the context of plane (i), the geometry undergoes a renewed contraction, thereby stabilising the flow and concentrating the turbulence kinetic energy distribution towards the centre. At an operating pressure of 4 bar, a pronounced turbulence core has been observed to form in the outlet region. In summary, the geometric effects (90° turning, expansion, and contraction) yielded analogous flow characteristics across all pressure levels. As the operating pressure increased, the magnitude of the turbulence kinetic energy, the spatial extent of its distribution and the prominence of its peak regions all became more pronounced.

CONCLUSION

The present study investigates the internal flow characteristics of a spray nozzle utilised in plant protection machinery. The investigation is conducted under three distinct operating pressures (2, 3, and 4 bar), employing the CFD method as the investigative approach. In the numerical analyses, particular attention was given to the flow behaviour in the 90° sharp turning regions, at points of sudden diameter change and at the outlet surface. The results of the velocity distribution study indicate that the flow accelerates in specific regions and develops into an asymmetric pattern throughout the system when it undergoes a 90° change in direction within the nozzle body. This finding demonstrates that the acceleration observed in the flow is primarily influenced by the geometric configuration, particularly in the turning and expansion regions. A thorough examination of the pressure distributions indicated that geometric variations and directional changes within the system gave rise to pronounced asymmetries in the pressure field. In particular, the pressure irregularities observed in planes (c)-(d) and (h) were interpreted as indicators of complex flow structures arising from turbulence, turning motions, and diameter transitions. It was determined that the turbulence kinetic energy increases markedly in regions where turning and sudden diameter changes occur. It is evident that these turbulence intensities have a substantial impact on the quality of flow and exit profiles within the nozzle body. The findings demonstrate that enhancements in spray characteristics can be achieved without altering the structural design of the spray nozzle. Instead, optimisation of operating parameters, such as pressure, can be sufficient to enhance performance. This finding is of significance for achieving effective, controlled, and homogeneous spray performance in agricultural applications.

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ÖZET

İnsanlığın başlangıcından bu yana bitkiler geleneksel tıpta kullanılmıştır. *Helichrysum* cinsindeki birçok tür tıbbi özellikler sergiler ve geleneksel tıpta kullanılmaktadır. Asteraceae, bitkiler alemindeki en büyük familyalardan biri ve aynı zamanda en çok endemik tür barındıran familyadır. Toplam 489 endemik tür barındıran Asteraceae familyasının endemizm oranı %36,3'tür. Asteraceae familyası üyeleri dünyanın hemen hemen her yerine dağılmıştır. Özellikle Amerika'nın güneybatısında, Meksika'da, Brezilya'nın güneyinde, Akdeniz Bölgesi'nde, güneybatı Asya'da, Orta Asya'da, Güney Afrika'da ve Avustralya'da bulunmaktadır. Helichrysum Gaertner, dünya çapında yaklaşık 500 türe sahip, oldukça yaygın bir Asteraceae familyası cinsidir. Türler, yüksek morfolojik çeşitlilikleri nedeniyle birçok alt türe ayrılmaktadır. Helichrysum türlerine Güney Avrupa, Güneybatı Asya, Güney Hindistan, Güney Afrika, Sri Lanka, Avustralya ve Madagaskar ev sahipliği yapmaktadır. *Helichrysum* cinsi, Türkiye florasında 20 farklı tür içeren toplam 26 taksonla temsil edilmektedir. Bu türlerin 14'ünün Türkiye'ye endemik olması dikkat çekicidir. *Helichrysum pallasii* (Spreng.) Ledeb. hem süs bitkilerinde hem de geleneksel tıpta kullanılmaktadır. Tıbbi bitkilerden elde edilen özler ve uçucu yağlar, bitkilerin kimyasal yapısını, antibakteriyel ve diğer tedavi edici özelliklerini incelemek için dünya çapındaki laboratuvarlarda kullanılmaktadır. Rize'nin Anzer yaylasından alınan *H. pallasii*'nin toprak üstü kısımlarının sekonder uçucu metabolit içeriği incelenmiştir. GC-MS cihazı kullanılarak otuz farklı bileşen tanımlanabilmiştir. Heptadekan (%9,79), İzofitol (%9,32), Fiton (%9,31), Heksadekan (%6,82), Oktadekan (%5,05), Miristat etil (%4,27) ve alfa Himachelen (%4,11), önemli biyolojik aktivite gösteren dikkate değer bileşenlerdir.

Anahtar kelimeler: GC-MS, kimyasal bileşim, tıbbi bitkiler

SECONDARY VOLATILE METABOLITE COMPOSITION OF *Helichrysum pallasii* COLLECTED ANZER HIGHLAND/RİZE

ABSTRACT

Since the beginning of human existence, plants have been utilised in traditional medicine. Many species in the genus *Helichrysum* exhibit medicinal properties and are used in traditional medicine. Asteraceae is one of the largest families in the plant kingdom and also the family that contains the most endemic species. The endemism rate of the Asteraceae family, which contains a total of 489 endemic species, is 36.3%. Members of the Asteraceae family are distributed almost everywhere on earth. It is especially found in the southwest of America, Mexico, the south of Brazil, the Mediterranean Region, southwest Asia, Central Asia, South Africa and Australia Helichrysum Gaertner is a genus in the Asteraceae family that is quite common, with about 500 species worldwide. The species are separated into many subspecies due to their high morphological variation. Southern Europe, South-West Asia, South India, South Africa, Sri Lanka, Australia, and Madagascar are home to Helichrysum species. The genus *Helichrysum* is represented in Turkish flora by a total of 26 taxa, which include 20 different species. Remarkably, 14 of these species are endemic to Türkiye. *Helichrysum pallasii* (Spreng.) Ledeb. is employed both ornamentally and in traditional medicine. Extracts and essential oils from medicinal plants are being used in labs all around the world to study the chemical makeup, antibacterial, and other therapeutic qualities of plants. The secondary volatile metabolite content of aerial portions of *H. pallasii* that were taken from the Anzer highland of Rize was examined. Using GC-MS device thirty distinct components could be identified. Heptadecane (9,79%), Isophytol (9,32%), Phytone (9,31%), Hexadecane (6,82%), Octadecane (5,05%), Myristate ethyl (4,27%), and alpha Himachelene (4,11%) were notable constituents that exhibited significant biological activity.

Key words: GC-MS, chemical composition, medicinal plants

INTRODUCTION

One of the largest families in the kingdom of plants, Asteraceae also has the highest number of endemic species. With 489 endemic species, the Asteraceae family has an endemism rate of 36.3% (Güner, 2013). The Asteraceae family is found practically everywhere on the planet. Southwest America, Mexico, southern Brazil, the Mediterranean region, southwest Asia, Central Asia, South Africa, and Australia are among the regions where it is most prevalent (Bremer, 1994).

There are 600 species of the genus *Helichrysum* in the Asteraceae family worldwide, however only 27 taxa—15 of which are endemic—represent this species in Turkey's Flora. (Bayer et al., 2007; Şenol et al., 2011; Davis et al., 1975; Davis et al., 1988; Güner et al., 2000). Additionally, several *Helichrysum* species can be found in Australia, Sri Lanka, southern India, and Southwest Asia (Lourens et al., 2008). Members of the genus *Helichrysum* (Asteraceae) are often dwarf perennial shrubs or aromatic herbs (Van Vuuren et al., 2006) that are grown on sandy or loamy soils at elevations ranging from sea level to 1700 m (Perrini et al., 2009; Mancini et al., 2011; Leonardi et al., 2013).

According to Davis and Kupicha (1975), Helichyrsum pallasii (Spreng.) Ledeb. is found at elevations of 1700–3600 meters on steppe and rocky slopes.

For a variety of biological effects, including antioxidant (Czinner et al., 2001; Tepe et al., 2005), antimicrobial activity (Albayrak et al., 2010), and anti-inflammatory (Sala et al., 2003), the plants are typically used in traditional medicine and are preferred as a herbal tea in Türkiye and other parts of the world.

H.pallasii collected from the Anzer Highland of Rize was investigated regarding its secondary volatile metabolite composition using SPME supported GC-MS device.

MATERIAL AND METHODS

Plant Material and Pre-Analysis Preparation

Helichrysum pallasii was collected from its natural habitat in the Anzer Highland, Rize (Türkiye). (2561m, 40°32'7"N - 40°30'9"E). Aerial parts of Helichrysum pallasii collected at the flowering time were used as plant material (Fig. 1).



Fig. 1: Collecton site of *Helichrysum pallasii* (Anzer/Rize)

Coordinate information of the location where the plants were collected was taken with the Garmin etrex 30x device.

The samples were dried in a fan oven until they reached constant weight (40°C for 3 days). The dried samples were then stored in a cold storage facility (+4°C). After being ground in a grinder, the dried samples were weighed to 0.2 grams for volatile component analysis

GC/MS Analysis

Volatile component analysis was performed using the SPME (Solid Phase Microextraction) method on a Shimadzu GC/MS-OP2020 instrument located in the Plant Analysis Laboratory of the Faculty of Agriculture at Recep Tayyip Erdoğan University. SPME analysis is a convenient method performed with a ground, dry sample without the need for solvents. The method is based on the absorption of essential oils by a fused silica fiber coated with a polymeric stationary phase, followed by desorption of the absorbed substances by heating at the injection port. (Fig. 2).



Fig2: SPME supported GC-MS device

Helium (1 mL/min) was used as the carrier gas in GC-MS analyses performed by electrospray ionization (EI) with the CP 5MS (30 m × 0.25 mm internal diameter, 0.25 µm film thickness). The oven was set to operate at a rate of 2 ℃/min from 40 ◦C to 240 ℃ and then at an isothermal temperature of 220 ℃ for 20 minutes. The temperature of the injector and detector was 240 °C. The compounds were identified by comparing their linear retention indices (LRIs) with a series of n-hydrocarbons and by comparing their retention times with those of pure original samples. The alkane series is C8-C24 or 2.5. Mass spectra were taken at 70 eV, and area normalization was used to calculate the percentage composition. After the compounds were separated on the gas chromatography column, each ion-mass spectrum was recorded, and the compounds were identified using the Shimadzu FFNSC library (Flavor & Fragrance Natural & Synthetic Compounds GC/MS Library).

RESULTS

Using GC-MS device twenty eight distinct components could be identified. Heptadecane (9,79%), Isophytol (9,32%), Phytone (9,31%), Hexadecane (6,82%), Octadecane (5,05%), Myristate ethyl (4,27%), and alpha Himachelene (4,11%) were notable constituents that exhibited significant biological activity (Table 1, Figure 1).

Table 1: Volatile oil constituents detected in *H. pruinatum* collected from the Cimil Highland in Rize

Rank	**Volatile Oil Compound (%)**	
1	Tetradecane	1,37
2	β-Caryophyllene	3,29
3	**α-Himachalene**	**4,11**
4	α-Curcumene	2,39
5	β-Selinene	1,17
6	α-Zingiberene	1,70
7	σ-Cadinene	1,90
8	γ-Cadinene	2,62
9	Tridecylaldehyde	1,87
10	Germacrene B	1,58
11	Tridecyl alcohol	2,00
12	**Hexadecane**	**6,82**
13	γ-Eudesmol	2,40
14	Hedione	3,45
15	(E)-citronellyl tiglate	1,22
16	α-Bisabolol oxide B	2,81
17	Octyl 2-Furan carboxylic acid	3,85
18	**Heptadecane**	**9,79**
19	Methyl Myristate	1,45
20	α-Bisabolone oxide A	3,59
21	Octyl caprylate	2,44
22	Pentadecanol	1,21
23	**Ethyl myristate**	**4,27**
24	**Octadecane**	**5,05**
25	**Phytone**	**9,31**
26	Nonadecane	3,86
27	**Isophytol**	**9,32**
28	Eicosane	1,35
Total	**100%**	

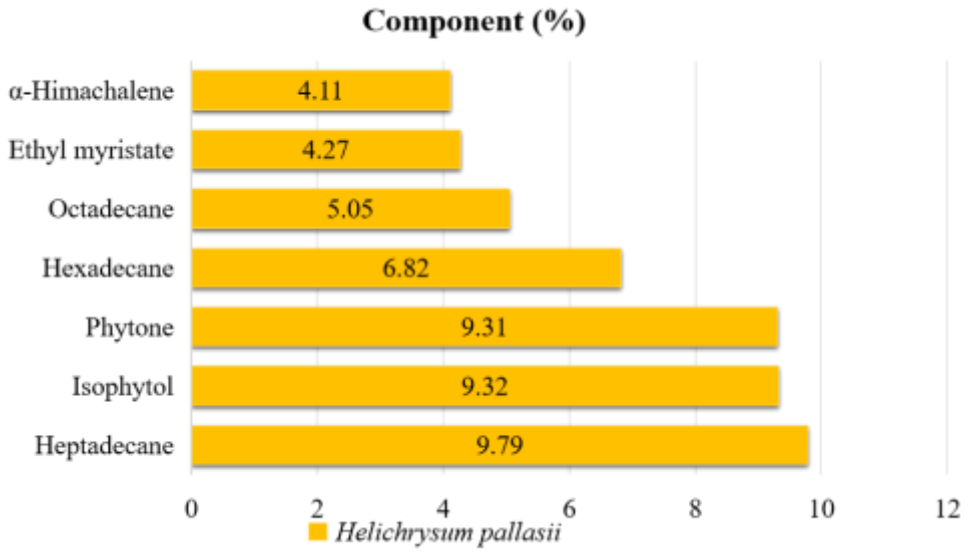

Fig. 3: Volatile oil constituents with high ratios detected *H. pallasii* collected from the Anzer Highland in Rize

Volatile components are displaying important biological activities, which can be seen in Table 2.

Table 2: Biological activities of some selected volatile oil components

Component	**Biological activity**	**References**
Heptadecane	antimicrobial	Bai et al. (2024)
Isophytol	antioxidant, anti-inflammatory, and antimicrobial effects.	Islam et al. (2018)
Phytone	antimicrobial	Lima et al. (2020)
Hexadecane	Antibacterial and antioxidant activity	Yogeswari et al. (2012)
Octadecane	antimicrobial activity	Kayode et al. (2018)
Ethyl Myristate	Antibacterial and antifungal activity	Jumina et al. (2019)
α-Himachelene	Antibacterial activity	Elbouzidi et al. (2025)

DISCUSSION

Yurteri et al. (2021) found α-Springene (34.89%), (-)-Isoledene (7.11%), δ-Selinene (5.79%), Aristolen (5.09%), β-Caryophy (4.76%) and α-Patchoulene (4.74%) as main components in flowers of *H. pallasii*.

Studies about the volatile oil composition of this species seems to be rare.

The yield and composition of volatile oil are influenced by a number of factors, including plant genetics, growth stage, geographic and environmental factors (such as climate, altitude, and soil type), agricultural practices and methods (such as plant density, water availability, and harvesting time), plant part used, extraction technique, and storage conditions (Mugao, 2004).

H.pallasii samples should be collected from different locations to provide more data and further conclusions.

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SECONDARY VOLATILE METABOLITE COMPOSITION OF *Hypericum pruinatum* COLLECTED FROM RİZE

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ÖZET

Hypericum L. (Sarı kantaron, Hypericaceae) cinsi, Antarktika hariç dünyanın her kıtasında doğal olarak yetişen 484 tür içermektedir. Bu cinse ait bitkiler farmakolojide oldukça önemlidir. *Hypericum* cinsi, Türkiye florasında yaygın olarak bulunmaktadır. Türkiye, 43'ü endemik olan 89 türüyle Hypericum cinsi için önemli bir merkezdir. Bu cinsin üyeleri farmakolojide oldukça önemlidir; özellikle *Hypericum perforatum* L., bol miktarda bulunan sekonder metabolitleri ve fitokimyasallarının sergilediği biyoaktiviteler nedeniyle kapsamlı bir şekilde incelenmiştir. *H. pruinatum* Boiss. And Bal., Türkiye'nin yüksek rakımlarındaki (1500-2500 m deniz seviyesi) volkanik yamaçlarda ve kayalık çıkıntılarda doğal olarak yetişen çok yıllık otsu bir bitkidir. Bu nadir tür, dağılım alanı Kuzey Türkiye ve Gürcistan ile sınırlıdır. Önceki çalışmalarda, *H. pruinatum*' un iyi belgelenmiş hiperisin, hiperforin, organik asitler ve flavonoid içeriğiyle büyük bir farmasötik potansiyele sahip olduğu bildirilmiştir. *H. pruinatum*' un toprak üstü kısımları Rize'den toplanmıştır. Sekonder uçucu metabolit bileşimi, SPME destekli GC-MS cihazı kullanılarak analiz edilmiştir. Önemli biyolojik aktiviteler gösteren 31 farklı sekonder uçucu yağ bileşeni tespit edilmiştir. En dikkat çekici bileşenler Cadina-1(6),4-dien <10betaH-> (%13,80), delta Cadinene (%11,7), beta Chamigrene (%9,68), beta Selinene (%9,36), gama Cadinene (%11,97), Hendacane (%7,47) ve alfa Copaene (%4,48) olmuştur.

Anahtar kelimeler: GC-MS, kimyasal bileşim, tıbbi bitkiler

RIZE' DEN TOPLANAN *HYPERICUM PRUINATUM*' UN UÇUCU YAĞ KOMPOZISYONU

ABSTRACT

The genus *Hypericum* L. (St. John's wort, Hypericaceae) includes 484 species, naturally occurring on every continent in the world except Antarctica. Herbs belonging to this genus are very important in pharmacology. The Hypericum genus is well represented in the Turkish flora Türkiye is an important center for the genus Hypericum with the presence of 89 species, of which 43 are endemic. Members of this genus are very important in pharmacology; in particular, *Hypericum perforatum* L. has been studied extensively for its abundant secondary metabolites and for the bioactivities exhibited by its phytochemicals. *H. pruinatum* Boiss. And Bal. is a perennial herbaceous plant which grows naturally in igneous slopes and rock ledges at high altitudes (1500–2500 msea level) of Türkiye. This is a rare species, distribution area of which is limited to Northern Türkiye and Georgia. In previous studies, *H. pruinatum* was reported to have great pharmaceutical potential with its well documented contents of hypericin, hyperforin, organic acids, and flavonoids. Aerial parts of *H. pruinatum* was collected from Rize. Its secondary volatile metabolite composition was analyzed using SPME supported GC-MS device. 31 different secondary volatile oil components were detected displaying important biological activities. The most remarkable components were Cadina-1(6),4-diene <10betaH-> (13,80 %), delta Cadinene (11,7 %), beta Chamigrene (9,68 %), beta Selinene (9,36 %), gamma Cadinen (11,97 %), Hendacane (7,47 %) and alpha Copaene (4,48 %).

Key words: GC-MS, chemical composition, medicinal plants

INTRODUCTION

Numerous civilisations were known to have existed in Anatolia, a well-known region in Turkey. Because of these facts, people have settled in this area, contributing to the current richness of culture. Additionally, Turkey has a variety of meteorological and geological conditions that result in a wide diversity of plants. Three plant geographical regions can be found in Turkey: the Mediterranean, Irano-Turanian, and Euro-Siberian. Compared to European nations, their geomorphology, topography, soil diversity, and geological altitude variations range from 0 to 5,000 meters. They have deep valleys, unique ecosystem species, and are less impacted by the ice age (Anonymous 2007).

The medicinal use of *Hypericum* species dates back 2,400 years, and its wound-healing effects, in particular, have been known since the 5th century BC. In the 1st century AD, the famous Greek physicians Galen and Dioscorides identified *H. perforatum* as a diuretic and wound-healing herb and recommended it for the treatment of menstrual disorders (Çırak and Kurt, 2014).

According to Istikoqlou et al. (2010), famous British botanists Gerard (1597) and Withering (1796) reported that Native American Indian tribes were well acquainted with Hypericum species and had used these plants as antipyretics and cough medicines for centuries.

Hypericum species have been used as a healing herb for centuries to relieve pain caused by nervous disorders, menstrual cramps, sciatica, arthritis, and stomach ailments, as well as to treat some skin conditions (Kaçar and Azkan, 2010).

The *Hypericum* L. (Hypericaceae) family is widely distributed and has flourished in a variety of settings across the globe. There are around 484 species in this genus worldwide (Meseguer and Sanmartín, 2012). Türkiye is a major *Hypericum* species gene center. According to the most recent revision, Turkey's flora contains 96 species of Hypericum, 46 of which are endemic (Guner et al., 2012). According to reports, the Aegean and Central Anatolia Region has more endemic species in Eastern and Southeastern Anatolia, whereas the Mediterranean Region has the highest number of endemic Hypericum species (Akgöz, 2013).

Numerous *Hypericum* species have been utilised in traditional medicine throughout the world, including Türkiye (Guclu et al., 2019). Numerous biological characteristics, including antidepressant (Butterweck et al., 2002), antibacterial, antioxidant, antiviral (Dall'Agno etal., 2003), antifungal (Cakir et al., 2005), and anticancer effects (Guclu et al., 2019), have been documented for Hypericum species. Additionally, a number of conditions, including bedwetting (Baytop, 1999), eczema (Tahir et al., 2017), Alzheimer's disease, haemorrhoids (Baytop, 1999), digestive problems (Kültür, 2007) gastric disorders, cardiovascular diseases (Kültür, 2007), wound healing (Öztürk et al., 2007), and burns (Baytop, 1999).

H. pruinatum collected from the Anzer Cimil Highland of Rize was investigated regarding its volatile oil composition using SPME supported GC-MS device.

MATERIAL AND METHODS

Plant Material and Pre-Analysis Preparation

H. pruinatum sample was collected from İkizdere-Cimil Highland(1995m, 40°44'3"N-40°46'37"E (Fig. 1)

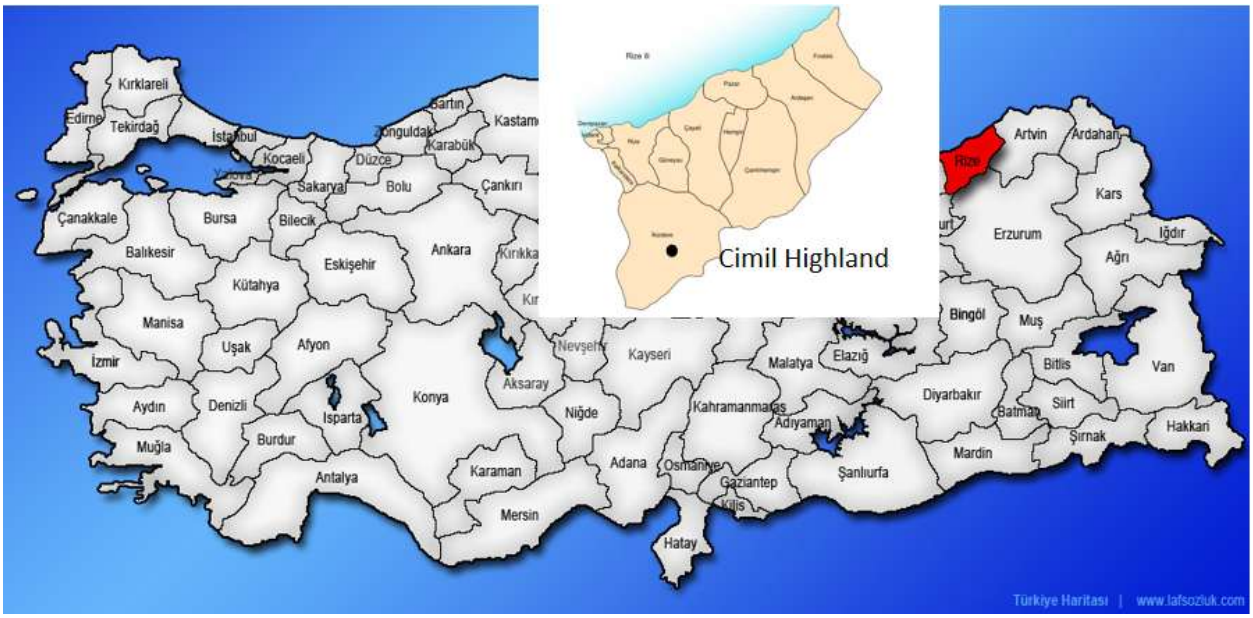

Fig. 1: Collecton site of *Hypericum pruinatum* (Cimil/Rize)

Coordinate information of the location where the plants were collected was taken with the Garmin etrex 30x device.

The samples were dried in a fan oven until they reached constant weight (40°C for 3 days). The dried samples were then stored in a cold storage facility (+4°C). After being ground in a grinder, the dried samples were weighed to 0.2 grams for volatile component analysis.

GC/MS Analysis

Volatile component analysis was performed using the SPME (Solid Phase Microextraction) method on a Shimadzu GC/MS-OP2020 instrument located in the Plant Analysis Laboratory of the Faculty of Agriculture at Recep Tayyip Erdoğan University. SPME analysis is a convenient method performed with a ground, dry sample without the need for solvents. The method is based on the absorption of essential oils by a fused silica fiber coated with a polymeric stationary phase, followed by desorption of the absorbed substances by heating at the injection port. (Fig. 2).



Fig2: SPME supported GC-MS device

Helium (1 mL/min) was used as the carrier gas in GC-MS analyses performed by electrospray ionization (EI) with the CP 5MS (30 m × 0.25 mm internal diameter, 0.25 µm film thickness). The oven was set to operate at a rate of 2 ℃/min from 40 ◦C to 240 ℃ and then at an isothermal temperature of 220 ℃ for 20 minutes. The temperature of the injector and detector was 240 °C. The compounds were identified by comparing their linear retention indices (LRIs) with a series of n-hydrocarbons and by comparing their retention times with those of pure original samples. The alkane series is C8-C24 or 2.5. Mass spectra were taken at 70 eV, and area normalization was used to calculate the percentage composition. After the compounds were separated on the gas chromatography column, each ion-mass spectrum was recorded, and the compounds were identified using the Shimadzu FFNSC library (Flavor & Fragrance Natural & Synthetic Compounds GC/MS Library).

RESULTS

Volatile oil constituents detected in *H. pruinatum* collected from the CimilHighland in Rize is shown in Table 1 and Fig . 1. Totally 31 volatile oil components could be detected using GC-MS analysis.

Table 1: Volatile oil constituents detected in *H. pruinatum* collected from the Cimil Highland in Rize

Rank	**Volatile Oil Compound (%)**	
1	**Hendecane**	**7.47**
2	Tridecane	2.76
3	alfa Cubebene	1.06
4	**alfa Copaene**	**4.48**
5	beta Elemene	0.80
6	Tetradecane	0.60
7	alfa Gurjunene	2.74
8	beta Cedrene	2.59
9	Aromadendrene	1.,4
10	alfa Patchoulene	0.50
11	alfa Humulene	1.00
12	Alloaromadendrene	2.99
13	**10-β(H)-Cadina-1(6),4-diene**	**13.80**
14	alfa Amorphene	1.32
15	**beta Selinene**	**9.36**
16	**beta Chamigrene**	**9.68**
17	**delta Cadinene**	**8.74**
18	**Gamma Cadinene**	**11.97**
19	Caryophyllene oxide	0.66
20	Hexadecane	1.89
21	Viridiflorol	0.64
22	alfa Acorenol	0.58
23	Epi alfa Muurolol	1.21
24	delta Eudesmol	1.95
25	alfa Bisabolol	2.03
26	Heptadecane	2.52
27	Octadecane	0.80
28	Phytone	0.56
29	Nonadecane	2.06
30	Heneicosane	1,42
31	Tetracosane	0.79
	Total	100%

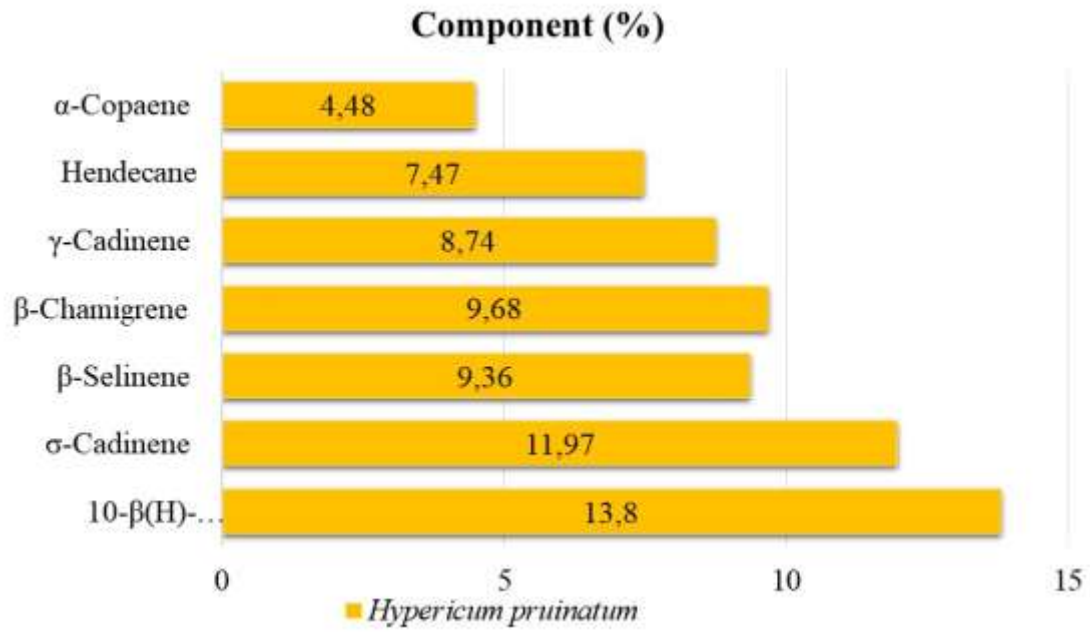

Fig. 3: Volatile oil constituents with high ratios detected *H. pruinatum* collected from the Cimil Highland in Rize

31 different secondary volatile oil components were detected displaying important biological activities. The most remarkable components were Cadina-1(6),4-diene <10betaH-> (13,80 %), delta Cadinene (11,97 %), beta Chamigrene (9,68 %), beta Selinene (9,36 %), gamma Cadinene (8,74 %), Hendacane (7,47 %) and alpha Copaene (4,48 %).

Biological activities are displaying important biological activities, which can be seen in Table 2.

Table 2: Biological activities of some selected volatile oil components

Cadina-1(6),4-diene <10betaH-	antimicrobial activity	Kačániová et al. (2022)
δ-Cadinene	Antibacterial, antimicrobial and antioxidant activity	Kačániová et al. (2022)
β-Chamigrene	antibacterial activities and cytotoxic activities	Dias et al. (2005)
β-Selinene	Antibacterial activity	Keawsa-arda et al. (2012)
γ-Cadinene	Antioxidant activity	Kundu et al. (2013)
Hendecane	Anti-Allergic and Anti-Inflammatory Activity	Choi et al. (2020)
α-Copaene	antioxidant and antigenotoxic activity	Turkez et al. (2014)

DISCUSSION

In the literature, Cirak & Bertoli (2013) detected β-selinene (15%), caryophyllene oxide (9%), β-caryophyllene (8%), and γ-muurolene (7%) in *H. pruinatum* volatile oil.

Akdeniz et al. (2023) published Germacrene D (22.47%), α-cadinol (12.73%), and δ-cadinene (9.59%) for *H. pruinatum.*

Factors affecting volatile oil yield and composition include plant genetics, growth stage, geographical and environmental conditions (like climate, altitude, and soil type), agricultural methods and practices (plant density, water availability, and harvesting time), plant part used, extraction method, and storage condition (Mugao, 2004).

To provide more data, *H. pruinatum* samples should be collected from different locations.

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FULL BRIDGE EVİRİCİLERDE GİRİŞ RİPPLE DAVRANIŞININ KAPASİTÖR KULLANIMI İLE AZALTILMASI

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ÖZET

Bu çalışmada, full bridge evirici devresinin giriş hattında oluşan ripple değerleri incelenmiş ve bu dalgalanmaların elektrolitik ve film kapasitörler yardımıyla nasıl azaltılabileceği gösterilmiştir. Ripple, eviricinin giriş DC hattında istenmeyen dalgalanmalara sebep olmakta ve sistem performansını olumsuz etkilemektedir. Deneysel olarak gerçekleştirilen ölçümlerde, yalnızca elektrolitik kapasitör kullanıldığında yüksek genlikli giriş dalgalanmaları gözlenirken, uygun değerlerde elektrolitik ve film kapasitör birlikte kullanıldığında ripple seviyesinin önemli ölçüde azaldığı tespit edilmiştir. Elde edilen sonuçlar, evirici tasarımlarında DC link kapasitörlerinin kritik bir rol oynadığını ve doğru kapasitör seçiminin sistem güvenilirliğini, verimini ve elektromanyetik uyumluluğunu artırdığını ortaya koymaktadır.

Anahtar Kelimeler: Full Bridge Inverter, Giriş Ripple, Elektrolitik Kapasitör, Film Kapasitör, DC Link, Güç Elektroniği

REDUCTION OF INPUT RIPPLE BEHAVIOR IN FULL BRIDGE INVERTERS BY USING CAPACITORS

ABSTRACT

In this study, the input ripple behavior of a full-bridge inverter circuit is investigated, and the effectiveness of electrolytic and film capacitors in reducing these ripples is demonstrated. Input ripples on the DC link not only decrease system efficiency but also increase thermal stress, electromagnetic interference (EMI), and total harmonic distortion (THD). Experimental measurements show that while large electrolytic capacitors are effective in suppressing low-frequency ripple, adding film capacitors significantly reduces high-frequency oscillations observed on the MOSFET drain–source voltage waveforms. The results highlight that the combined use of electrolytic and film capacitors improves the reliability, efficiency, and electromagnetic compatibility of inverter systems.

Keywords: Full Bridge Inverter, Input Ripple, Electrolytic Capacitor, Film Capacitor, DC Link, Power Electronics

1. Giriş

Güç elektroniğinde eviriciler (invertörler), doğru akımı (Direct Current) alternatif akıma (Alternating Current) dönüştüren birimlerdir. Çıkış gerilimi, uygulama yerine göre değişiklik gösterebilir. Türkiye'de şebekelerde 220 V, 50 Hz. AC çıkış kullanılırken, askeri standartlarda 115 V ve 400 Hz. AC çıkış tercih edilmektedir. Çok çeşitli evirici topolojileri mevcuttur. Ancak askeri uygulamalarda sağlamlık, az komponent kullanımı ve basitlik nedeniyle tam köprü (full bridge) evirici topolojisi sıkça tercih edilmektedir. Aynı zamanda bu topoloji hem endüstriyel hem de evsel uygulamalarda yaygın olarak kullanılmaktadır [6], [1].

Eviricilerin güvenilir çalışması, yalnızca anahtarlama devresinin tasarımına, yazılım tasarımına veya sistem mimarisine bağlı değildir. Giriş DC hattının kalitesine de doğrudan bağlıdır. Evirici girişinde oluşan dalgalanmalar (ripple), sistemin verimliliğini ve ömrünü etkileyen kritik parametrelerden biridir. Yüksek genlikli ripple; yarı iletken elemanlarda ek ısınmaya, elektromanyetik girişim (EMI) seviyelerinin artmasına ve çıkış AC dalga formunda bozulmaya sebep olarak toplam harmonik bozulmayı (THD) yükseltebilir. Bu nedenle, giriş ripple'ının azaltılması yalnızca performans açısından değil, aynı zamanda güvenilirlik ve standartlara uyumluluk açısından da önemlidir [2], [4], [5].

Bu çalışmada, elektrolitik kapasitörlerin yanı sıra film kapasitörlerin evirici girişinde ripple azaltmadaki etkisi incelenmiştir. Osiloskop ölçümleri ile desteklenen deneysel sonuçlar, uygun kapasitör seçiminin giriş gerilimi üzerindeki dalgalanmaları önemli ölçüde düşürdüğünü göstermektedir. Böylece eviricinin daha kararlı çalıştığı ve sistemin uzun vadeli dayanıklılığının arttığı ortaya konmuştur [3].

2. Teorik Arka Plan

2.1. Kapasitör Tiplerinin Evirici Giriş Ripple'ına Etkisi

Evirici DC girişinde kullanılan kapasitörlerin türü, sistemin dinamik performansını doğrudan belirler. Pratikte üç farklı kapasitör tipi yaygın olarak kullanılmaktadır: elektrolitik, film ve seramik kapasitörler. Bu kapasitörlerin her biri farklı frekans aralıklarında bastırma etkisine sahiptir ve bu nedenle tamamlayıcı şekilde kullanıldığında sistem performansı önemli ölçüde artar [2], [8], [10].

Elektrolitik kapasitörler, yüksek kapasite değerleri sayesinde düşük frekanslı dalgalanmaları bastırmada etkilidir. Ancak yüksek ESR ve ESL değerlerine sahip olduklarından, anahtarlama sırasında oluşan yüksek frekanslı geçici rejimlerde yeterince hızlı tepki veremezler. Bu durum, drain–source dalga formlarında gözlenen ani tepe gerilimlerinin (overshoot) ve ring davranışlarının temel sebeplerinden biridir [2], [6], [7], [8], [9].

Film kapasitörler düşük ESR ve düşük ESL özellikleri sayesinde yüksek frekanslı akım bileşenlerini çok daha etkin şekilde süzer.Elektrolitik kapasitörlere paralel bağlandıklarında DC baranın empedansı geniş bir frekans bandında düşmektedir. Böylece hem düşük frekans hem de yüksek frekans bileşenleri aynı anda bastırılabilir. Deneysel sonuçlarda film kapasitör eklenmesiyle tepe drain–source gerilimlerinin azalması doğrudan bu etkiye işaret etmektedir. Seramik kapasitörler, özellikle sınıf I dielektrik yapıda olanlar (C0G, NP0) çok düşük ESL ve ESR sunarak birkaç MHz'e kadar olan frekanslarda etkin filtreleme sağlar. Ancak kapasiteleri küçük olduğu için tek başlarına kullanılamaz, film kapasitörlerle birlikte tamamlayıcı rol oynarlar [2], [6], [8], [9], [10].

Bu nedenle modern evirici tasarımlarında DC link genellikle çok seviyeli bir kapasitör bankasından oluşturulur [2], [10]:

Yüksek kapasite → elektrolitik

Orta frekans → film

Çok yüksek frekans → seramik

Bu yaklaşım, güç elektroniği literatüründe "çok katmanlı kapasitör yaklaşımı (multi-layer capacitor strategy)" olarak anılmakta ve özellikle geniş bant aralıklı yarı iletkenlerin (SiC / GaN) kullanıldığı uygulamalarda zorunlu hale gelmektedir [2], [8].

2.2. Ripple Teorisi

Güç elektroniği devrelerinde ripple, doğru akım (DC) hatlarında görülen istenmeyen dalgalanmalardır. Bu dalgalanmalar; eviricinin yüksek frekansta anahtarlama yapması, yük değişimleri ve enerji depolama elemanlarının sınırlı kapasitesi nedeniyle oluşur. Evirici, yapısı gereği dinamik bir yük gibi davrandığından, besleme kaynaklarının bu yapıya uygun tasarlanması gerekir.

Ripple genliği temel olarak kapasitör değerine, yük akımına ve anahtarlama frekansına bağlıdır. Matematiksel olarak:

$$(1)\ \Delta V = \frac{I_{ripple}}{C * f}$$

- ΔV: Kapasitör uçlarında oluşan dalgalanma gerilimi (V)
- I_{ripple}: Ripple akımı (A)
- C: Kullanılan kondansatör kapasitesi (F)
- f: Anahtarlama frekansı veya ilgili harmonik frekans (Hz)

Formülden görüldüğü üzere, kapasitör değeri arttıkça dalgalanma gerilimi azalır. Bu yüzden inverter DC girişinde genellikle yüksek değerli elektrolitik kondansatörler tercih edilir. Elektrolitik kondansatörler büyük kapasite değerleri sunarak düşük frekanstaki dalgalanmaları etkin şekilde bastırır.

Bununla birlikte, yalnızca kapasite değeri değil, kondansatörün ESR (Equivalent Series Resistance) değeri de ripple üzerinde belirleyici bir parametredir. Düşük ESR değerine sahip kapasitörler daha düşük ısı üretir ve ripple'ı daha etkin azaltır. Ripple akımı kapasitör üzerinden geçtiğinde, ESR nedeniyle ek bir gerilim düşümü oluşur:

$$(2)\ V_{ESR} = I_{ripple} * ESR$$

Dolayısıyla toplam ripple gerilimi şu şekilde ifade edilebilir:

$$(3)\ \Delta V_{total} = \frac{I_{ripple}}{C * f} + I_{ripple} * ESR$$

Bu nedenle kapasitör seçimi yapılırken yalnızca kapasite büyüklüğüne değil, aynı zamanda ESR değerine ve ömür parametrelerine de dikkat edilmelidir. Bu özellikleri sayesinde film kapasitörler sıklıkla tercih edilmektedir.

3. Deneysel Çalışmalar

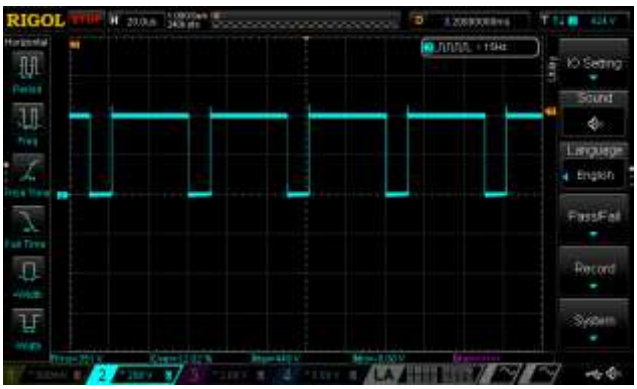
Bu çalışmada, evirici girişindeki ripple davranışı doğrudan DC linkten ölçülmek yerine, MOSFET drain–source uçlarında gözlemlenmiştir. Bu dalga formları, DC baradaki dalgalanmaların ve parazitik endüktansların etkilerini daha net göstermektedir.

Deney düzeneğinde 400 µF toplam elektrolitik kapasite (8×39 µF + 2×47 µF) kullanılmış, ESR değerini düşürmek için kapasitörler paralel bağlanmıştır. Buna ek olarak 2 adet 10 µF film kapasitör eklenmiştir. Anahtarlama frekansı 20 kHz olarak seçilmiştir. Ölçümler 100:1 passive prob ile MOSFET'in VDS uçlarında yapılmıştır.

Farklı değerlerde film kapasitör eklenerek MOSFET drain–source dalga formları incelenmiş ve sonuçlar Tablo 3'de verilmiştir.



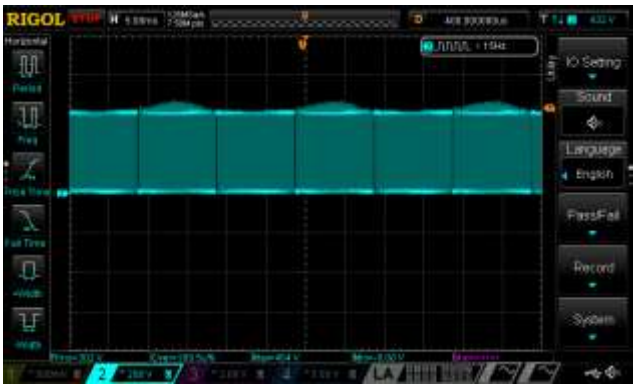
Şekil 1 (a)



Şekil 1 (b)

Şekil 8. 2kW MOSFET drain–source dalga formları 0x film kapasitesi: (a) Time/Div: 5 ms, (b) Time/Div: 20 µs

Drain Source değeri maksimum 464 Vdc değerine çıkmaktadır. Sistemin daha stabil çalışması için ESR değerinin daha da düşmesi için yüksek frekansları daha iyi bastırmak için anahtarlama elemanlarının bacaklarına yakın film kapasitörler eklenerek deneyler gerçekleştirilmiştir. Deneylere ait osiloskop görüntüleri ve elde edilen sonuçlar aşağıda sunulmaktadır.

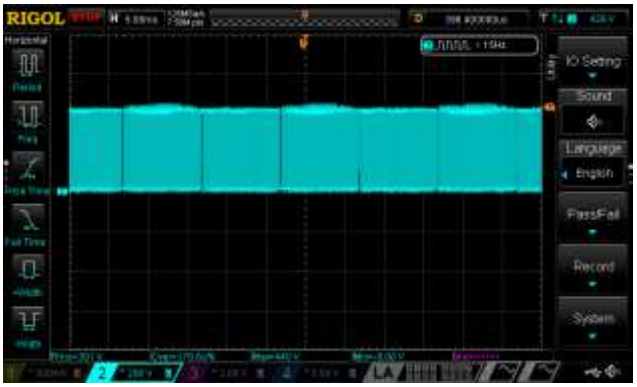


Şekil 2 (a)

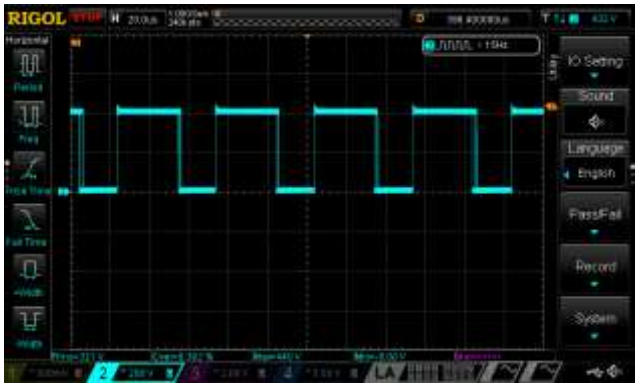


Şekil 2 (b)

Şekil 9. 2kW MOSFET drain–source dalga formları 2x 1 nF film kapasitesi: (a) Time/Div: 5 ms, (b) Time/Div: 20 µs



Şekil 3 (a)

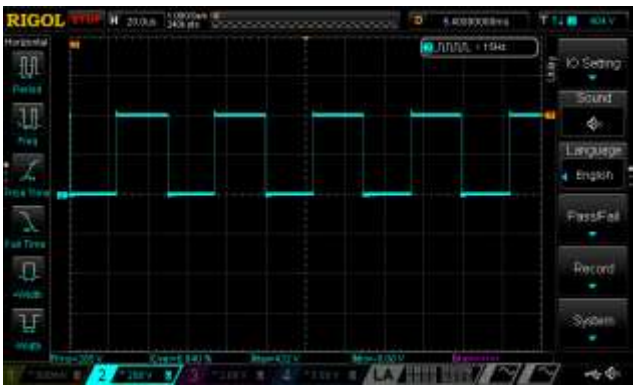


Şekil 3 (b)

Şekil 10. 2kW MOSFET drain–source dalga formları 2x 15 nF film kapasitesi: (a) Time/Div: 5 ms, (b) Time/Div: 20 µs



Şekil 4 (a)

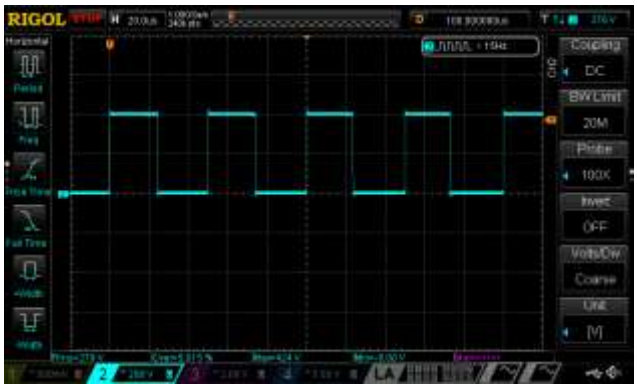


Şekil 4 (b)

Şekil 11. 2kW MOSFET drain–source dalga formları 2x 330 nF film kapasitesi: (a) Time/Div: 5 ms, (b) Time/Div: 20 µs



Şekil 5 (a)



Şekil 5 (b)

Şekil 12. 2kW MOSFET drain–source dalga formları 2x 4.7 μF film kapasitesi: (a) Time/Div: 5 ms, (b) Time/Div: 20 µs

Tablo 3. MOSFET drain–source gerilimine film kapasitör değerlerinin etkisi

DC bara değeri	Film kapasitör değeri	Ölçülen Drain-Source Gerilimi
400 µF Elektrolit + 20 µF Film	0 µF	464 Vdc
400 µF Elektrolit + 20 µF Film	1 nF x 2	464 Vdc
400 µF Elektrolit + 20 µF Film	15 nF x 2	440 Vdc
400 µF Elektrolit + 20 µF Film	330 nF x 2	432 Vdc
400 µF Elektrolit + 20 µF Film	4.7 µF x 2	424 Vdc

4. Sonuçlar ve Tartışma

Bu çalışmada, tam köprü evirici devresinde giriş ripple davranışı MOSFET drain–source uçlarındaki dalga formları üzerinden incelenmiştir. Ölçümler, girişte kapasitör bulunmadığında drain–source geriliminde yüksek genlikli zıplamalar ve belirgin ring davranışı oluştuğunu göstermiştir. Bu durum, DC link enerjisinin ani akım değişimlerini karşılamakta yetersiz kaldığını ve parazitik endüktansların baskın hale geldiğini ortaya koymaktadır.

Elektrolitik kapasitörlere paralel bağlanan film kapasitörler, düşük ESR ve düşük ESL özellikleri sayesinde yüksek frekanslı salınımları etkin biçimde bastırmıştır. Bu sayede drain–source dalga formunda daha düşük tepe değerler elde edilmiş, hızlı sönümlenen ring davranışı gözlenmiştir.

Sonuçlar, evirici tasarımında elektrolitik ve film kapasitörlerin birlikte kullanımının hem düşük frekanslı giriş ripple'ını hem de yüksek frekanslı zıplamaları bastırmak açısından kritik önem taşıdığını göstermektedir. Bu yaklaşım, sistem güvenilirliğini artırmakta, yarı iletkenlerin ömrünü uzatmakta ve elektromanyetik uyumluluğu geliştirmektedir.

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PREDICTION OF EFFECTIVE DIFFUSIVITY IN NANOCELLULOSE-BASED SANDWICH-TYPE MEMBRANES FOR POLYMER ELECTROLYTE FUEL CELLS

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ABSTRACT

Polymer electrolyte fuel cells (PEFCs) have gained considerable attention owing to their high efficiency, fast start-up capability, and low-temperature operation. Their ability to generate electricity cleanly, with water as the only byproduct, makes them strong candidates for transportation, stationary power, and portable energy applications. The large-scale deployment of PEFCs, however, depends strongly on the performance and durability of their components, particularly the polymer electrolyte membrane (PEM). Perfluorosulfonic acid (PFSA) membranes such as Nafion® remain the benchmark due to their high proton conductivity and acceptable stability, yet their high cost, limited high-temperature robustness, and classification as persistent PFAS chemicals motivate the development of more sustainable alternatives. Nanocellulose-based sandwich-type membranes have recently been proposed as a promising solution, as the introduction of gas-barrier interlayers can suppress radical formation by reducing reactant crossover, thereby enhancing membrane durability. Membrane diffusivity plays a critical role in PEFC operation because it governs water transport, directly influencing membrane hydration, proton conductivity, and overall performance; insufficient diffusivity can cause dehydration or flooding, leading to substantial ohmic and mass-transport losses. In this study, the effective diffusivity of nanocellulose-based sandwich-type membranes with varying interlayer thicknesses is predicted using experimentally measured hydrogen crossover current densities within a resistances-in-series framework. Understanding and accurately predicting these diffusivity values provides a foundation for rational membrane design, enabling the development of next-generation PEMs with improved water management, durability, and fuel cell performance.

Keywords*:* Polymer electrolyte fuel cells; Effective diffusivity; Nanocellulose; Sandwich-type membranes; Hydrogen crossover; Membrane durability

Introduction

The global energy landscape is undergoing a rapid transition toward cleaner and more sustainable technologies as nations work to mitigate climate change and reduce greenhouse gas emissions. In this context, hydrogen has emerged as a promising energy carrier because it can be produced from renewable resources and used without generating carbon emissions at the point of use [1]. Its versatility (being usable in gaseous, liquid, or solid forms) makes hydrogen suitable for a wide range of applications, including transportation, industrial processes, and stationary power generation [2]. Among these applications, fuel cell electric vehicles (FCEVs) are expected to play a central role in achieving net-zero targets in the automotive sector [3].

Proton exchange membrane fuel cells (PEFCs) are one of the most commercially advanced fuel cell technologies. A typical PEFC assembly consists of bipolar plates, gas diffusion layers (GDLs), catalyst layers, and a polymer electrolyte membrane (PEM). Nafion, a perfluorosulfonic acid (PFSA) ionomer, has long been the benchmark PEM material due to its high proton conductivity, mechanical robustness, and chemical stability [4]. Despite these advantages, membrane durability remains a major barrier for long-term PEFC operation. Reactive oxygen species (ROS), particularly hydroxyl (HO·) and hydroperoxyl (HOO·) radicals generated from hydrogen peroxide in the presence of divalent metal ions, can attack and degrade the PFSA backbone, leading to thinning, pinhole formation, and ultimately membrane failure.

To address these challenges, numerous strategies have been investigated to enhance membrane resistance to chemical degradation [5] [6] [7]. These include the development of hydrocarbon-based ionomers with inherently higher oxidative stability and the incorporation of reinforcing fillers. Nanocellulose has recently attracted significant attention as a sustainable reinforcement material due to its abundance, biodegradability, low cost, and excellent mechanical properties. It has been widely used as an additive in PEMs, typically at low loadings [8].

A recent study by Yang et al. [9] introduced a new membrane design in which a nanocellulose (NC)-poly(vinyl sulfonic acid) (PVS) blend layer is sandwiched between two Nafion films to serve as an internal gas barrier (Fig. 1). This structure was shown to significantly mitigate hydrogen crossover and enhance chemical durability, demonstrating the potential of sandwich-type membranes for long-lasting PEFC operation. However, the performance of such membranes is strongly dependent on the thickness of the interlayer, and the previous work considered only a single thickness. Numerical optimization therefore requires knowledge of how the gas barrier layer thickness influences hydrogen crossover.

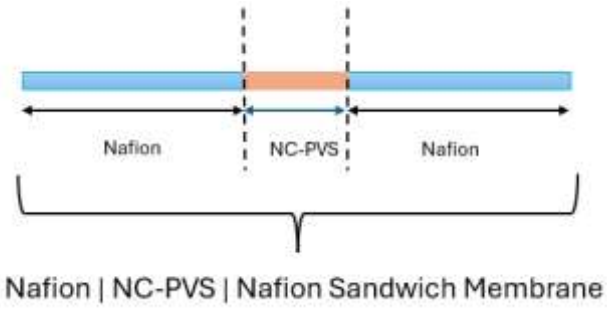

Fig. 1 Schematic representation of nanocellulose-based sandwich-type membrane.

Hydrogen crossover is governed largely by the effective diffusivity of hydrogen through the ionomer and any intermediate layers. Yet, no literature data exist for the effective diffusivity of hydrogen in nanocellulose-based sandwich-type membranes. To address this gap, the present

study proposes an approach to estimate the effective diffusivity of hydrogen in these layered membranes. The method first evaluates the effective diffusivity of hydrogen in pure Nafion and in NC-PVS membranes using available experimental data. These values are then used to estimate the effective diffusivity for multilayer sandwich configurations with varying interlayer thicknesses.

The results provide essential insights for future design and optimization of nanocellulose-based sandwich-type membranes. Ultimately, establishing a reliable approach to predict effective diffusivity will support performance-driven thickness optimization and guide the development of durable PEMs for next-generation PEFCs.

Methodology

Hydrogen crossover current density (I_{cross}) depends on the effective diffusivity of hydrogen in the ionomer ($D_{H_2}^{\text{eff}}$) and the total membrane thickness (t_{total}). It can be calculated using the following expression:

$$I_{cross} = \frac{nF\, D_{H_2}^{eff} \Delta p_{H_2}}{RT t_{total}} \tag{1}$$

where n is the number of electrons involved in hydrogen oxidation, F is Faraday's constant (96,485 C/mol), R is the universal gas constant (8.314 $J/(mol.K)$), T is the operating temperature of the fuel cell (80 ℃) and Δp_{H_2} is the hydrogen partial pressure gradient between the anode and cathode.

For a multilayer membrane, the total diffusive resistance in the through-plane direction is the sum of the individual resistances of each layer. Thus, the total diffusive resistance of the nanocellulose-based sandwich-type membrane can be written as [10]:

$$\frac{t_{total}}{D_{H_2}^{eff}} = \frac{t_{NC-PVS}}{D_{NC-PVS}} + \frac{t_{total} - t_{NC-PVS}}{D_{Nafion}} \tag{2}$$

where t_{NC-PVS} is the thickness of NC-PVS interlayer, D_{NC-PVS} is the hydrogen diffusivity in the NC-PVS interlayer and D_{Nafion} is the hydrogen diffusivity in the Nafion layers. Rearranging Eq. (2) yields an explicit expression for the effective hydrogen diffusivity of the sandwich-type membrane:

$$D_{H_2}^{eff} = \frac{t_{total}}{\frac{t_{NC-PVS}}{D_{NC-PVS}} + \frac{t_{total} - t_{NC-PVS}}{D_{Nafion}}} \tag{3}$$

Hydrogen diffusivity in polymer electrolytes depends on temperature, pressure, and relative humidity. Therefore, accurate estimation of $D_{H_2}^{\text{eff}}$ under the relevant operating conditions is essential for predicting hydrogen crossover current density. The approach outlined above provides a means to estimate the effective hydrogen diffusivity of nanocellulose-based sandwich-type membranes and, consequently, to evaluate their impact on PEFC performance.

Results and Discussion

In the experimental study given in Ref [9], the average hydrogen crossover current densities for pure Nafion and the NC–PVS sandwich membrane (with an NC–PVS ratio of 10:1 in the interlayer) were measured as 3.5 and 2.7 mA/cm², respectively. Using Eq. (1), the effective diffusivity of hydrogen in Nafion was calculated to be 4.8×10^{-10} m^2/s, which is consistent with values reported in the literature [11]. Under the same operating conditions (80 °C and 95%

relative humidity), the effective diffusivity of hydrogen in the NC–PVS-based sandwich membrane was determined to be 2×10^{-10} m^2/s.

Fig. 2 illustrates the variation of effective hydrogen diffusivity as a function of total membrane thickness for several NC-PVS interlayer thicknesses (0.1, 0.5, 2, and 4 μm). In all cases, the effective diffusivity increases with total membrane thickness due to the larger contribution of the outer Nafion layers, which exhibit higher hydrogen diffusivity than the NC-PVS interlayer.

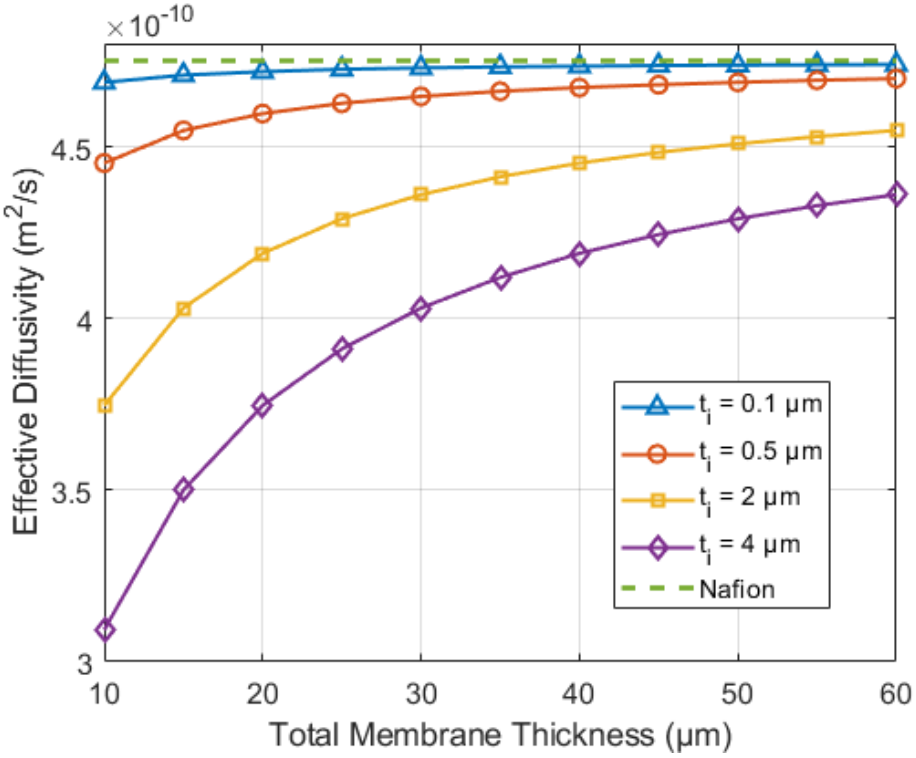

Fig. 2 Effective diffusivity of hydrogen vs total membrane thickness at different NC-PVS interlayer thicknesses.

For the 0.1 μm interlayer, the calculated effective diffusivity remains close to the Nafion benchmark because the NC–PVS layer represents only a small fraction of the overall resistance. The diffusivity slightly increases with increasing total thickness. This corresponds to only almost 1.1% deviation from the Nafion value across the entire thickness range, indicating that very thin NC–PVS layers minimally influence hydrogen crossover.

Increasing the interlayer thickness to 0.5 μm results in a more noticeable reduction in diffusivity, particularly for thinner membranes. At 10 μm, the effective diffusivity decreases to 4.5×10^{-10}m²/s, representing an approximately 7% reduction relative to Nafion. However, as membrane thickness increases, the influence of the interlayer diminishes. At 60 μm, the diffusivity reaches 4.7×10^{-10}m²/s, approaching the Nafion benchmark.

A much stronger effect is observed for 2 μm interlayer thickness. At 10 μm, the effective diffusivity drops to 3.7×10^{-10}m²/s, corresponding to an about 22% reduction compared to Nafion. As the membrane becomes thicker, diffusivity gradually increases, reaching 4.5×10^{-10}m²/s at 60 μm. Although the trend is similar to thinner interlayers, the diffusivity remains substantially below the Nafion value across the full thickness range.

The impact is most pronounced for the 4 μm interlayer, where the NC–PVS layer accounts for a large portion of the total membrane thickness. The effective diffusivity is reduced to

3.1×10^{-10}m²/s at 10 µm (approximately 36% lower than Nafion) indicating a strong gas-barrier effect. Even at 60 µm, the diffusivity reaches only 4.4×10^{-10}m²/s, still approximately 9% below Nafion. This demonstrates that increasing interlayer thickness effectively suppresses hydrogen permeation.

Conclusions

This study proposes an approach to predict the effective diffusivity of hydrogen in nanocellulose-based sandwich-type membranes. These findings highlight an important design trade-off. In the literature, reducing membrane thickness is a common strategy for mitigating ohmic losses and improving fuel cell performance. However, thin membranes are significantly more sensitive to the presence of an NC–PVS barrier layer. This reduction directly translates to lower hydrogen crossover current density, enhancing chemical durability. At larger total thicknesses, the differences between interlayer cases become smaller, suggesting that performance benefits from a gas-barrier layer are more impactful in ultra-thin membranes. Future work will focus on predicting PEFC performance with these membranes and optimizing interlayer thickness using a one-dimensional mathematical model.

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PESOPTIMIZATION OF CNN HYPERPARAMETERS IN PLANUS DIAGNOSIS USING META-INTUITIVE METHODSOPTIMIZATION

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ÖZET

Pes planus, ayak kavsinin normalden düşük ya da tamamen düz olmasıyla karakterize edilen bir ayak deformitesidir ve tedavi edilmediğinde ağrıya ve yürüme bozukluklarına neden olabilir. Bu çalışmada, pes planus (düz tabanlık) tespitine yönelik ayak taban görüntülerinin derin öğrenme tabanlı yöntemler ve meta-sezgisel optimizasyon algoritmaları ile otomatik olarak sınıflandırılması amaçlanmıştır. Çalışmada kullanılan veri seti, 137 normal ve 421 pes planus olmak üzere toplam 558 ayak taban görüntüsünden oluşmaktadır. İlk aşamada, MobileNetV2 tabanlı, transfer öğrenme yaklaşımı kullanan bir evrişimsel sinir ağı (CNN) model olarak tasarlanmış ve standart hiperparametrelerle eğitilmiştir. Bu temel model için test doğruluğu 0.8359 olarak elde edilmiştir. İkinci aşamada, CNN mimarisine ait temel hiperparametreler (öğrenme oranı, dropout oranı, taban modelinin eğitilebilir katman oranı, veri artırma şiddeti vb.) meta-sezgisel yöntemler olan genetik algoritma (GA), gri kurt optimizasyonu (GWO) ve parçacık sürü optimizasyonu (PSO) ile optimize edilmiştir. Optimizasyon sürecinde, her hiperparametre kümesi için model eğitilmiş doğruluk değeri hesaplanmıştır. Elde edilen sonuçlar, GA ve GWO'ya kıyasla en yüksek performansın PSO ile optimize edilen CNN yapısında elde edildiğini ve test doğruluğunun 0.8984' e yükseldiğini göstermiştir. Sonuç olarak, meta-sezgisel yöntemlerle hiperparametre optimizasyonunun, pes planus gibi klinik açıdan önemli ayak deformitelerinin otomatik tespitinde CNN tabanlı sistemlerin başarımını artırdığı; özellikle PSO yaklaşımının tıbbi görüntü sınıflandırma problemlerinde etkili ve umut vadeden bir optimizasyon aracı olduğu ortaya konmuştur.

Anahtar Kelimeler: Pes planus, Derin öğrenme, Evrişimsel sinir ağı (CNN), Metasezgisel optimizasyon, Tıbbi görüntü sınıflandırma

PES PLANUS TANISINDA CNN HİPERPARAMETRELERİNİN META-SEZGİSEL YÖNTEMLERLE OPTİMİZASYONU

ABSTRACT

Pes planus is a podiatric condition characterized by a reduced or absent foot arch. If left untreated, this condition can result in discomfort and walking impairments. The objective of this study is to develop a system that can automatically classify foot arch images for the purpose of identifying pes planus, or flat feet. This will be achieved by employing deep learning-based methods and meta-heuristic optimization algorithms. The dataset utilized in the present study encompasses a total of 558 foot sole images, comprising 137 images of normal feet and 421 images of pes planus feet. In the initial phase, a convolutional neural network (CNN) model was developed and trained using standard hyperparameters. This model was based on MobileNetV2 and utilized a transfer learning approach. The test accuracy for this baseline model was obtained as 0.8359. In the subsequent phase, the fundamental hyperparameters of the CNN architecture (learning rate, dropout rate, the proportion of trainable layers in the base model, intensity of data augmentation, etc.) were optimized through the utilization of meta-heuristic methodologies, namely genetic algorithm (GA), grey wolf optimization (GWO), and particle swarm optimization (PSO). During the process of optimization, the model training accuracy value was calculated for each hyperparameter set. The findings demonstrated that the CNN structure optimized using PSO yielded the highest performance, surpassing GA and GWO, and the test accuracy increased to 0.8984. In conclusion, meta-intuitive methods for hyperparameter optimization have been shown to improve the performance of CNN-based systems in the automatic detection of clinically significant foot deformities such as pes planus. Specifically, the PSO approach has been demonstrated to be an effective and promising optimization tool for medical image classification problems.

Keywords: Pes planus, Deep learning, Convolutional neural networks (CNN), Metaheuristic optimization, Medical image classification

1-INTRODUCTION

The human foot is considered to be one of the most complex anatomical structures in the body, performing a vital function in the proper functioning of the lower limbs. This structure is capable of adapting to different surfaces and can support the entire body weight by providing the flexibility and support necessary for the person to stand and move (walk) [1]. Pes planus, or flat feet, is a deformity that frequently occurs in this complex structure. It is characterized by the collapse of the medial longitudinal arch, the outward rotation of the heel, and the prominence of the bony protrusion on the inner side of the ankle bone. The collapse of the medial longitudinal arch has the potential to induce alterations in the structure of the lower limbs, which can result in the manifestation of pain, various injuries, and an increased risk of limited movement. A range of studies have demonstrated that the prevalence of pes planus varies between 10.27% and 17.1%. It has been observed in the extant literature that there are notable variations in the prevalence of foot disorders among different racial and ethnic groups, which are associated with variations in foot structure. While some studies have found that the condition resolves spontaneously within the first ten years of life, other research indicates that it becomes permanent with advancing age. For instance, the prevalence of pes planus in individuals aged 18 to 25 was reported to be 29%, and it was observed that this condition did not disappear with age. In light of these findings, early foot examinations are of paramount importance in order to prevent the condition from becoming a problem for individuals in later years [2].

The posterior tibial tendon performs the function of a powerful internal rotator of the foot and plays a critical role in both maintaining the medial longitudinal arch of the foot and counteracting posterior foot reversion deformity. [3]. Consequently, any dysfunction in the tendon may result in the development of pes planus. For these reasons, early diagnosis is important to prevent the progression of pes planus in individuals. Radiography is currently the preferred primary imaging modality for diagnosing pes planus. This method facilitates the use of various radiographic measurements for the purpose of determining the severity of the deformity. However, the extent to which these different radiological parameters are associated with specific damage to the posterior tibial tendon (PTT) and the supporting structures of the medial longitudinal arch of the foot has not yet been fully determined [4]. At present, the diagnosis of tendon dysfunction and associated secondary supporting structure injuries is largely based on magnetic resonance imaging (MRI) [5].

Deep learning, a branch of machine learning and artificial intelligence, has precipitated substantial advancements in the healthcare sector, most notably in the domain of orthopedics. The capacity of deep learning to analyze intricate algorithms and derive conclusions has led to its significant role in domains such as diagnostic processes, treatment strategies and the prediction of surgical outcomes. In the domain of medicine, deep learning has emerged as a particularly salient method in the analysis of medical visual materials. The utilization of deep learning algorithms, endowed with the capacity to employ neural networks, has been demonstrated to facilitate the successful detection of intricate structures in imagery, such as X-rays or magnetic resonance (MR) scans. This capacity enables the diagnosis of various disorders [6].

A review of the literature reveals that studies aimed at diagnosing pes planus have employed a variety of methods, including visual assessment, footprint analysis, pressure distribution measurements, and radiographic angles. It is evident that a number of these studies employ image processing or traditional machine learning approaches. In recent years, however, there

has been a significant increase in the number of studies utilizing deep learning techniques based on CNNs for the classification of pes planus and other foot deformities.

CNNs are a popular deep learning architecture for image-based tasks. The efficacy of CNNs in this domain can be attributed to their simple yet effective design. In the contemporary era, there exists a plethora of models that are founded upon the fundamental CNN design, which serve a diverse array of purposes [7]. The distinguishing feature of CNN architecture that sets it apart from classical neural networks is its capacity to substantially minimize the number of parameters necessary during the feature extraction stage [8]. In a CNN, various components such as the number of convolutional layers, the number of kernels, and the dropout rate are considered CNN parameters. A significant benefit of CNN architectures is their capacity to operate with a suitable set of hyperparameters. However, this architecture presents a challenge in the selection of hyperparameters that will optimally solve the problem. Hyperparameter optimization is employed to address these challenges and to identify the most suitable solution. Nevertheless, given the considerable number of parameters, this process can be costly and time-consuming. It is customary for these hyperparameters to be configured manually. A variety of hyperparameter optimization algorithms have been employed to automate this adjustment process. When such modifications are performed with suitable algorithms, they have been shown to yield positive contributions in terms of time and cost for many studies [9].

In this study, a MobileNetV2-based CNN model, pre-trained on the ImageNet dataset, was applied to classify pes planus images. In the initial phase, the baseline CNN model was trained using a set of hyperparameters (learning rate, dropout rate, data augmentation intensity, etc.), and performance metrics such as accuracy were obtained on the test sets. Subsequently, to increase and improve the accuracy score achieved by this baseline model, the hyperparameters were optimized using metaheuristic optimization techniques such as Genetic Algorithm (GA), Grey Wolf Optimization (GWO), and Particle Swarm Optimization (PSO). For each metaheuristic algorithm, CNN models were retrained by testing different hyperparameter settings and combinations. The optimal GA, GWO, and PSO solutions derived from these combinations were subsequently evaluated on the test set, and the outcomes were contrasted with the baseline CNN model based on MobileNetV2.

A review of the literature reveals studies in which pes planus and metaseptic methods have been used in medical datasets. For instance;

In a study conducted by Kim and colleagues, a transfer learning-based method relying on deep learning was proposed for pes planus classification. In this study, a pre-trained architecture such as VGG16 was utilized, and a model exhibiting high prediction performance was created using data augmentation methods. The model was trained using a dataset consisting of a total of 176 images (88 pes planus and 88 normal feet). In order to ascertain the efficacy of this novel approach, a comparison experiment was conducted with a standard CNN model. The baseline CNN model demonstrated training, validation, and test accuracies of 77.27%, 61.36%, and 59.09%, respectively. In contrast, the proposed innovative model achieved training accuracy of 94.32%, validation accuracy of 86.36%, and test accuracy of 84.09%. In light of these findings, it is evident that the newly developed model attains markedly superior outcomes in terms of classification performance in comparison to the standard CNN model [10].

In a separate study conducted by Dogan and colleagues, the objective was to enhance the precision of flatfoot (pes planus) diagnosis. In order to achieve this objective, an innovative fusion model was developed by combining the VGG16 CNN architecture with the ViT-B/16 Vision Transformer. This hybrid model capitalizes on the local feature capture ability of CNNs and the global context understanding power of ViT structures, demonstrating higher

performance compared to current methods in the literature. Furthermore, researchers have employed ensemble learning methodologies to enhance the model's reliability and its capacity for generalization. The findings of the model, evaluated through a ten-fold cross-validation approach, substantiate its capacity to attain a commendable level of performance. The sensitivity recorded was 97.4%, the specificity 96.4%, and the F1 score 96.8% [11].

As posited by Aguerchi et al., breast cancer is among the most prevalent forms of cancer on a global scale. Medical imaging techniques are among the most critical methods used in the detection and diagnosis of breast cancer. CNNs, which are extensively employed in image classification tasks, present certain challenges in selecting the appropriate architecture and hyperparameters. This research has led to the development of a new CNN model that has the capacity to diagnose breast cancer with a high degree of accuracy from mammography images. The proposed model utilizes Particle Swarm Optimization (PSO) to enhance the CNN architecture and hyperparameters. The PSO-based CNN model demonstrated accuracy rates of 98.23% and 97.98% on the DDSM and MIAS datasets, respectively, showing better performance compared to similar studies in the literature [12].

2-MATERIAL AND METHODS

2.1 Data Set

In this thesis research, the dataset compiled by Gül and colleagues and publicly shared on the Kaggle platform was utilized [13,14]. The dataset under consideration comprises 842 X-ray images of 439 patients aged between 14 and 47 years who were referred to the Radiology Department of Elazığ Fethi Sekin City Hospital with suspected pes planus. The images were obtained using a Philips dual-detector digital X-ray machine (65 kV, 6.3 mAs) and stored in the data pool in JPG file format. However, the dataset was subject to a process of filtration, resulting in the exclusion of images deemed to be of substandard quality. Finally, the reduced dataset utilized in this study was organized using a data augmentation method to ensure class balance. Figure 1 presents a series of images drawn from the dataset.



Figure 1. Images from the data sets.

2.2 CNN Model

In the contemporary era, CNNs have become a prominent exemplar of artificial neural networks, owing to their remarkable efficacy in the domain of deep learning algorithms [15]. CNNs have been successful in completing a number of tasks that were previously considered to be impossible. These tasks include face recognition, autonomous vehicle operation, robotic perception, and various solutions in the healthcare sector. The provision of such conveniences

serves to demonstrate that CNN is one of the most groundbreaking and transformative technologies in existence today [16].

CNNs have been shown to offer distinct advantages over traditional artificial neural networks [17]. It has been demonstrated that the capacity to discern spatial and temporal relationships in input data without the necessity for human intervention constitutes a significant advantage [18]. The automatic feature extraction process of CNNs eliminates the need for this process, which must be done manually in traditional models. This increase in processing speed enables more accurate results in the studies conducted [17].

2.3 Metaheuristic Algorithms

The term "meta" has seen a marked increase in usage across various disciplines in recent years, typically signifying "beyond something itself" or "at a higher level." This concept, which remains without a precise and universally accepted mathematical definition, is referred to in the literature as meta-heuristic methods. These are defined as higher-level search strategies that manage, organize, or develop different heuristic methods [19]. Optimization algorithms are a class of computational methods that select from a given set of candidate solutions to achieve maximum results for the problem at hand, and do so continuously. Meta-heuristic algorithms represent a significant category of optimization methods [20]. The meta-heuristic algorithms employed in the present study are, respectively: Genetic Algorithms, Grey Wolf Optimization, and Particle Swarm Optimization.

2.3.1 Genetic Algorithm

The development of the genetic algorithm was informed by Darwin's theory of "survival of the fittest," which draws inspiration from the process of biological evolution [21]. The algorithm under discussion is fundamentally based on three main operations: selection, reproduction, and mutation. The survival of the fittest is the principle on which the selection phase is based. However, it also allows for the improvement of relatively undeveloped individuals and the transmission of this improvement to subsequent generations. Organisms in nature are characterized by a set of rules or plans that govern their characteristics. These small hereditary units are known as genes. Genes are known to form long sequences of DNA, known as chromosomes [22, 23]. In a standard Genetic Algorithm (GA), the initial set of potential solutions is generated using a random method. Subsequently, evolutionary operators are applied to transform this population; this cycle is repeated until a specified termination condition is met. The modeling of evolutionary mechanisms in natural settings has facilitated the utilization of this efficient and powerful system in optimization and search problems in engineering [23].

2.3.2 Grey Wolf Optimization

The Grey Wolf Optimization (GWO) algorithm mimics the social structure and hunting methods of gray wolves in their natural habitat. These wolves typically live in packs of 5 to 12 individuals in the wild [24]. The pack is usually led by leaders called Alphas, consisting of one male and one female. The Alpha makes decisions alone on important matters such as hunting plans or choosing resting places. However, it has been noted that in some cases, even the Alpha listens to other members and exhibits cooperative decision-making behavior. Beta wolves occupy the second position in the social hierarchy. Beta wolves are subordinate to the Alpha; they support the leader in the pack's daily affairs and decision-making processes. This individual advises the Alpha, maintains discipline within the pack, relays the leader's orders, and feeds back opinions from the group. At the bottom of the hierarchy are the Omega wolves. Omegas must obey all dominant members. Although they appear to be the least valuable members of the pack, it has been observed that when an Omega is missing, serious internal

turmoil arises within the group. There is also an intermediate level called Delta. Delta wolves obey the Alpha and Beta, but are in a higher position than the Omega [25].

2.3.3 Particle Swarm Optimization

The method called Particle Swarm Optimization (PSO) was developed and introduced by Russell C. Eberhart and James Kennedy [26]. This optimization technique was discussed in detail in a scientific paper co-authored by these two scientists and first published in 1995 [27]. Derived from the concept of swarm intelligence, this approach is based on research into the movement dynamics of flocks of birds and schools of fish. Birds searching for food either move randomly or travel together (in flocks) until they locate the exact location of the food source. When birds move from one area to another in search of food, an individual that can predict the location of food more accurately than others or has the best information usually emerges. During the search, birds constantly share this valuable information, especially the location of the best source, with each other, and eventually cluster around the area where the food is located, guided by this accurate information [26].

2.4 Performance Metrics

The evaluation of the success of artificial intelligence-based algorithms and the selection of the most effective prediction model is a significant area that has been examined in detail in the majority of the studies conducted. In this type of research, various evaluation metrics such as accuracy, precision, recall, and F1 score are generally used to demonstrate the best predictive solution developed. It is widely acknowledged that the prediction accuracy score is a pivotal metric for evaluating the efficacy of a model, as it provides a quantitative measure of its predictive capabilities. This criterion is one of the most popular used to determine the most appropriate prediction solution, regardless of the structure of the data set or the distribution of target classes [28]. The confusion matrix is a tool employed in prediction analysis that compares the results obtained by the model with the actual data. The utilization of a comparison table facilitates the calculation of vital performance metrics, including accuracy, precision, sensitivity, and the F1 score. The matrix structure under consideration contains four fundamental elements that arise in classification processes: True positives, false positives, true negatives and false negatives [29]. These elements are presented in the confusion matrix in Figure 2.

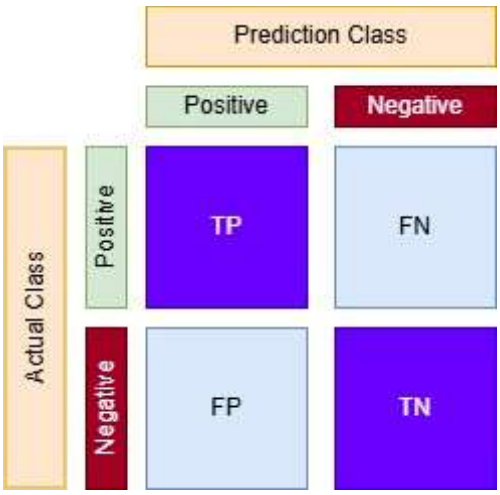

Figure 2. Confusion Matrix

3. EXPERIMENTAL RESULTS

This section presents a comparative analysis of CNN models optimized using Genetic Algorithm (GA), Grey Wolf Optimization (GWO), and Particle Swarm Optimization (PSO) parameters with the basic CNN model. In the context of the results obtained, the validation and test accuracy values of the models are shown in Figure 3.

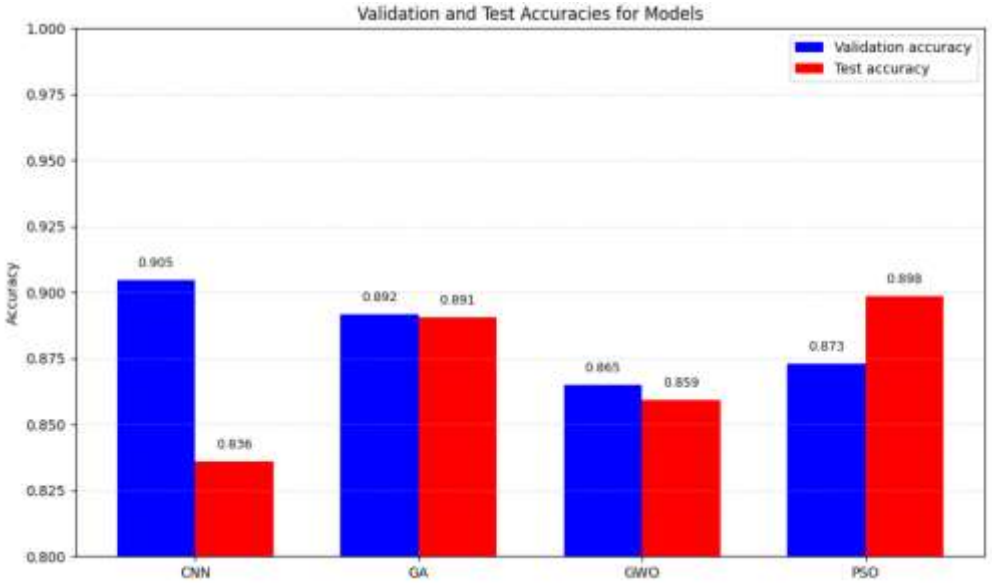

Figure 3. Validation and test accuracies of basic CNN and meta-heuristic-optimized CNN models

The validation and test success rates of the four proposed models are collectively presented in Figure 3. It is evident that the fundamental CNN model attained an accuracy level of approximately 90.5% in the validation dataset; nevertheless, its test accuracy persisted at around 83.6%. This discrepancy suggests that the fundamental model exhibits a satisfactory fit with the training and validation data, yet demonstrates limited capacity for generalization in the testing phase. In the model that has been optimized using the Genetic Algorithm (GA), the validation accuracy is 89.2%, while the test accuracy is approximately 89.1%. The observation that the validation and test performances are so close to each other indicates that the hyperparameters determined by GA adjust the model more evenly and reduce the risk of over fitting. In a similar vein, the validation accuracy of the model that was optimized using Grey Wolf Optimization (GWO) was recorded as 86.5%, while the test accuracy was 85.9%. Despite the fact that these values are lower than the results obtained with GA and Particle Swarm Optimization (PSO), the minor discrepancy between validation and test scores suggests that the model's generalization behaviour is stable.

In the context of the results obtained, the confusion matrices of the models are shown in Figure 4.

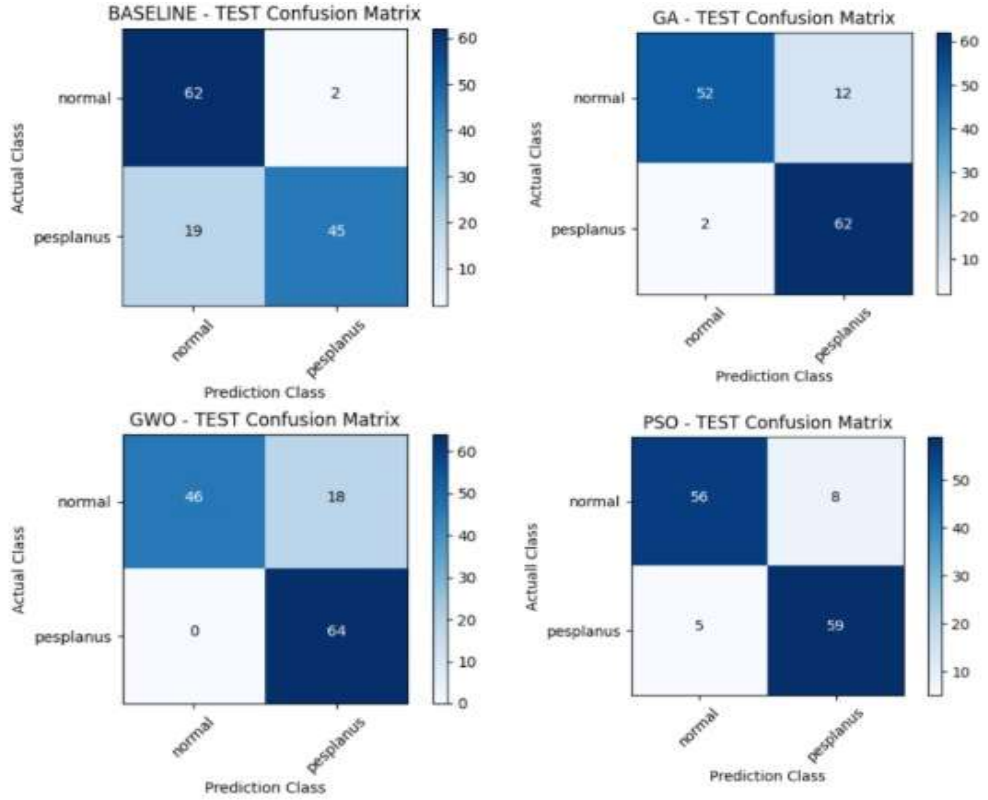

Figure 4. Confusion matrices of basic CNN and meta-heuristic-optimized CNN models

As illustrated in Figure 4, the confusion matrices for the test set of models that have been optimized with meta-heuristic algorithms, employing the basic CNN architecture, are displayed. While all four models generally produce successful results, there are significant differences in terms of error distribution and inter-class balance. In the fundamental CNN model, the normal class is predominantly classified correctly (62/64), whereas 19 pes planus examples are designated as normal (45/64 correct). This finding suggests that the model demonstrates a high level of proficiency in distinguishing between normal and pathological feet; however, it exhibits reduced sensitivity for pes planus, with occasional instances of "missing" the pathological class. In the GA-optimized model, misclassification in the pes planus class is significantly reduced, with only 2 pes planus examples being labeled as normal (62/64 correct). Conversely, 12 examples from the normal class are classified as pes planus. Consequently, the model obtained with the genetic algorithm increases sensitivity in pes planus detection while producing a marginally higher number of "false positives". The GWO-based model demonstrated an accuracy of 64/64 in correctly identifying the pes planus class in the test set, thus exhibiting no errors in this particular classification. However, 18 examples from the normal class were labeled as pes planus. This structure signifies a model profile with elevated pes planus sensitivity, a feature that could prove advantageous in screening scenarios where the precision of diagnosis is paramount. Conversely, the model that has been optimized with PSO evinces balanced performance in both classes. The model demonstrated a 56/64 accuracy in the normal class and a 59/64 accuracy in the pes planus class. It is noteworthy that the number of false negatives (pes planus classified as normal) and false positives were reduced to a more balanced level in comparison to other models. The findings indicate that the model which has been tuned with particle swarm optimization offers the most balanced solution in terms of overall accuracy and inter-class balance.

Table 1 presents performance metrics such as precision, sensitivity, F1-score, and accuracy for basic CNN and metaheuristic-optimized CNN models.

Table 1. Average performance metrics of basic CNN and meta-heuristic-optimized CNN models

	Precision	Recall	F1-Score	Accuracy
Baseline CNN	0.8614	0.8359	0.8330	0.8359
Genetic Algorithm	0.9004	0.8906	0.8900	0.8906
Grey Wolf Optimization	0.8902	0.8594	0.8565	0.8594
Particle Swarm Optimization	0.8993	0.8984	0.8984	0.8984

The following section presents a comparison of the mean performance metrics of models developed using the basic CNN model and metaheuristic algorithms (Genetic Algorithm (GA), Grey Wolf Optimization (GWO), and Particle Swarm Optimization (PSO)). These are set out in Table 1. The performance metrics of the fundamental CNN architecture were evaluated, yielding a precision of 0.8614, a recall of 0.8359, an F1-score of 0.8330, and an accuracy of 0.8359. The findings indicate that the model performs adequately in general, yet it exhibits a certain degree of inaccuracy when distinguishing between positive and negative classes, suggesting potential for enhancement. The performance metrics of the GA-optimized model demonstrated a substantial enhancement, with precision reaching 0.9004, sensitivity reaching 0.8906, F1-score reaching 0.8900, and accuracy reaching 0.8906. This increase, observed in all metrics when compared to the baseline CNN, indicates that GA combines hyperparameters such as learning rate, dropout rate, trainable layer ratio, and class balancing strategies in a more suitable combination, thereby improving the model's ability to predict true positives and true negatives. The model obtained with GWO reported a precision value of 0.8902, sensitivity of 0.8594, F1-score of 0.8565, and accuracy of 0.8594. Despite the enhancement in each metric of the GWO model in comparison to the fundamental CNN, it exhibited marginal inferiority to GA and PSO with regard to F1 and accuracy values. This result demonstrates that GWO exhibits a more cautious approach, particularly in certain class examples, and offers relatively balanced performance between sensitivity and precision. The model that was trained with PSO demonstrated the most balanced and highest performance of the four models, with precision of 0.8993, sensitivity of 0.8984, F1-score of 0.8984, and accuracy of 0.8984. The observation that the sensitivity and accuracy values in the PSO model are closely aligned suggests that the proportion of correctly classified examples is significant and that the model makes consistent generalizations across different classes. In conclusion, it can be stated that all metaheuristic algorithms have demonstrated an enhanced performance in comparison to the basic CNN architecture. In particular, the GA and PSO models have been shown to provide more effective solutions to the pes planus classification problem with high precision, sensitivity, F1, and accuracy values.

4- DISCUSSION

The dataset utilized in this study comprises foot images categorized into the "normal" and "pes planus" classes. The deep learning model was prepared for utilization by means of preprocessing these images. For the classification task, MobileNetV2, a CNN architecture pre-trained on ImageNet, was utilized as a foundation; fully connected layers were incorporated into this backbone to engineer a structure that would yield a two-class output. The findings unequivocally demonstrate that the fundamental CNN architecture exhibited suboptimal

performance in comparison to models that have been optimized through the utilization of metaheuristic algorithms. The CNN model demonstrated an approximate accuracy of 83.6%, with comparable metrics, including precision, sensitivity, and F1-score, being produced. A thorough examination of models that have been optimized with metaheuristic algorithms has revealed that all methods provide substantial enhancements in terms of accuracy and other performance indicators when compared to the fundamental CNN structure. The model that was optimized with the Genetic Algorithm (GA) achieved an accuracy score of approximately 89.1%. A significant increase in F1-score and sensitivity was recorded in comparison to the basic model. The model obtained with Grey Wolf Optimization (GWO) demonstrates an approximate accuracy of 85.9%. This model demonstrated a superior structural design in comparison to the fundamental CNN, particularly with regard to sensitivity and inter-class balance. In the field of machine learning, Particle Swarm Optimization (PSO) has been shown to demonstrate superior performance when compared to other algorithms, with an accuracy of approximately 89.8%. This performance is noteworthy for its consistency and reliability, making it a noteworthy contender in the search for optimal machine learning models. The PSO-based model has been demonstrated to reduce misclassification rates while maintaining class balance, thus resulting in a clinically more reliable classification profile. This fundamental CNN model functioned as the baseline for the duration of the study. However, in order to enhance the model's performance, the utilization of metaheuristic optimization algorithms was deemed to be a superior approach in comparison to the manual adjustment of hyperparameters. In this context, critical hyperparameters such as learning rate, dropout rate, trainable base layer ratio, data augmentation density, oversampling, and class weights have been automatically adjusted using Genetic Algorithm (GA), Grey Wolf Optimization (GWO), and Particle Swarm Optimization (PSO).

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HAYVAN SAĞLIĞI VE BESLENMESİNDE FİTOTERAPİ: FİTOTERAPİK BİTKİLER

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ÖZET

Fitoterapi, tedavi edici, hastalıkları iyileştirici ve hastalıkları önleyici olarak tanımlanmış, tıbbi bitkiden doğrudan doğruya; ya da bitkinin belli kısımlarından yararlanılarak gerçekleştirilen tedavi yöntemidir. Fitoterapi tarihsel olarak çok eski dönemlere, antik medeniyetlere kadar uzanmaktadır. İlk izlerine Mısır, Çin, Hindistan ve Yunan medeniyetlerinde rastlanır. Antik Mısır'da bitkisel ilaçlar, tıbbi uygulamalarda ve hayvanlardaki çeşitli rahatsızlıkların tedavisinde kullanılmıştır. On sekizinci yüzyılın sonları ve on dokuzuncu yüzyıl başlarında bitkilerin kimyasal içeriği hakkında fazla bir bilgi olmadığından bitkilerin, koruma ve tedavi edici etkileri yıllar boyunca elde edilmiş tecrübeleri temel almıştır. Günümüzde yapılan son araştırmalar ise bitkilerde bulunan sekonder matabolitler ve bu matabolitlerin hayvan verimi, sağlığı ve kalitesi üzerine olmuştur. Bu bileşikler hem rumen sağlığı hem de hayvansal üretim açısından önem ihtiva etmektedir. Fenolik bileşikler içeren bitkiler ile beslenen hayvanlarda yem tüketimi ile birlikte hayvansal ürünlerde verim ve kalite de artmaktadır. Sekonder metabolitler antioksidan ve antimikrobiyal özellikleri ile ruminant hayvanlarda şişkinlik ve asidoz gibi beslenme bozukluklarını kontrol altına almaktadır. Söz konusu metabolitler doğal antibiyotik olarak da işlevsel görev üstlenmektedir. Bu durum dışarıdan sentetik antibiyotik kullanılmasını sınırlandırırken, hayvan sağlığı, kalitesi, verimi açısından önem arz etmektedir. Ayrıca biyoaktif bileşenler hayvansal kaynaklı küresel ısınmaya azaltılmasına katkı sunması açısından da önem arz etmektedir. Fitoterapik özellik gösteren birçok bitki bulunmaktadır. Bu bitkilerin bazılarının tarımı yapılırken, bazıları ise doğada yabani formda bulunmaktadır. Bu derlemede, fitoterapinin hayvan sağlığı ve beslemesi açısından önemi ile fitoterapik bitkiler hakkında bilgi verilmesi amaçlanmıştır.

Anahtar kelimeler: Fitoterapi, , sekonder metabolit, hayvan sağlığı, hayvan besleme.

PHYTOTHERAPY IN ANIMAL HEALTH AND NUTRITION: PHYTOTHERAPEUTIC PLANTS

ABSTRACT

Phytotherapy is defined as a therapeutic method that utilizes medicinal plants directly, or certain parts of plants, for healing, treatment, and disease prevention purposes. The history of phytotherapy dates back to ancient times and early civilizations. Its first traces can be found in Egyptian, Chinese, Indian, and Greek civilizations. In ancient Egypt, herbal medicines were used in medical practices and for the treatment of various animal ailments. At the end of the eighteenth century and the beginning of the nineteenth century, there was limited knowledge about the chemical composition of plants; therefore, the protective and healing effects of plants were based on years of accumulated experience. Modern research, however, has focused on the secondary metabolites found in plants and their effects on animal productivity, health, and quality. These compounds are important for both rumen health and overall animal production.Animals fed with plants containing phenolic compounds show increased feed intake, as well as improvements in yield and quality of animal products. Secondary metabolites, with their antioxidant and antimicrobial properties, help control nutritional disorders such as bloating and acidosis in ruminants. These metabolites also act as natural antibiotics, thereby reducing the need for synthetic antibiotics and contributing positively to animal health, productivity, and product quality. In addition, bioactive compounds are significant due to their potential to reduce livestock-related global warming. There are many plants with phytotherapeutic properties-some are cultivated, while others grow naturally in the wild. This review aims to provide information about the importance of phytotherapy in terms of animal health and nutrition, as well as to introduce various phytotherapeutic plants.

Keywords: Phytotherapy, secondary metabolite, animal health, animal nutrition.

1. Giriş

Tıbbi nitelik taşıyan bitkiler, son yıllarda hayvan hastalıklarının tedavisinde alternatif bir yaklaşım olarak öne çıkmaya başlamıştır. Avrupa ve Asya kökenli tarihsel kaynaklarda bu bitkilerin hayvan sağlığı açısından önemi uzun zaman önce belirtilmiş olsa da, nicel verilere dayanan araştırmaların azlığı nedeniyle gerçek değerleri tam olarak ortaya konulamamıştır (Mayer ve ark., 2014). Günümüze kadar yapılan çalışmaların çoğu, bu bitkilerin tanımlanması, uçucu yağ bileşenleri ve insan sağlığına yönelik etkileri üzerinde yoğunlaşmıştır. Buna karşılık, hayvan besleme açısından taşıdıkları yem değeri konusunda oldukça sınırlı sayıda araştırma bulunmaktadır. Oysa bu bitkiler, çeşitli bakteriyel patojenlere karşı doğal antibiyotik özellik gösteren organik bileşikler içermektedir (Sipponen ve ark., 2012). Kowalczyk ve ark. (2013), hayvan beslenmesinde kullanılan dış kaynaklı antibiyotik katkılarının 2006 yılında yasaklanmasıyla birlikte, sekonder metabolitler bakımından zengin olan tıbbi bitkilerin antibiyotiklere potansiyel bir alternatif haline geldiğini ifade etmektedir.

Son yıllarda ruminant beslenmesine yönelik araştırmalar, sekonder metabolitlerin rumen fonksiyonları ve hayvansal performans üzerinde kritik bir role sahip olduğunu ortaya koymuştur (Patra ve ark., 2006; Lee ve ark., 2017; Rochfort ve ark., 2008). Dohi ve ark. (1997), fenolik bileşikler içeren bitkilerle beslenen hayvanlarda yem tüketiminin arttığını ve bunun üretim parametrelerine olumlu katkı sağladığını rapor etmiştir. Santos Neto ve ark. (2009) ile Frozza ve ark. (2013) ise bu bileşiklerin güçlü antioksidan ve antimikrobiyal özellikler taşıdığını vurgulamaktadır. Ayrıca flavonoidler ve fenolik bileşiklerin rumen fermentasyonunun düzenlenmesi, şişkinlik ve asidoz gibi beslenmeye bağlı sorunların kontrolünde etkili olduğu belirlenmiştir (Seradj ve ark., 2014; Paula ve ark., 2016).

Bu derlemede, fitoterapinin hayvan sağlığı ve beslemesi açısından önemi ile fitoterapik bitkiler hakkında bilgi verilmesi amaçlanmıştır.

2. Fitoterapi

Tarihte ilk kez Fransız hekim Henri Leclerc (1870-1955) tarafından kullanılan bir terim olan fitoterapi; tedavi edici, hastalıkları iyileştirici ve hastalıkları önleyici olarak tanımlanmış tıbbi bitkiden doğrudan doğruya; ya da bitkinin belli kısımlarından yararlanılarak gerçekleştirilen tedavi yöntemidir (Faydalıoğlu ve Sürücüoğlu, 2011). Fitoterapi insan ve hayvan sağlığı ile beslenmesinde önemli bir rol oynar. Doğal tedavi seçenekleri sunarak kimyasal ilaçlara alternatif oluşturur ve kimyasal ilaçların kullanımını azaltmaktadır.

Fitoterapi tarihsel olarak çok eski dönemlere, antik medeniyetlere kadar uzanmaktadır. İlk izlerine Mısır, Çin, Hindistan ve Yunan medeniyetlerinde rastlanmaktadır. Antik Mısır'da bitkisel ilaçlar, tıbbi uygulamalarda ve çeşitli rahatsızlıkların tedavisinde kullanılmıştır. Yine Babil–Asur tabletlerinde çok sayıda bitki (güzel avrat otu, tatula, keten, servi, sedir ağacı, incir ağacı, soğan) tedavi amaçlı kullanım açısından tanımlanmıştır (Makarska-Bialokoz, 2019).

Fitoterapi, insanlık tarihinin en eski dönemlerine uzanan bir uygulama olup, zamanla toplumların kültürel yapısına ve günlük yaşamına yerleşmiş, çoğu kişinin sorgulamadan benimsediği bir tedavi yöntemi hâline gelmiştir. Günümüzde dünya nüfusunun yaklaşık %80'inin tercih ettiği bitkisel tedaviler, Tıbbın babası kabul edilen Hipokrat da dâhil olmak üzere birçok önemli tarihi ismin katkılarıyla şekillenmiştir. Yüzyıllar önce tarif edilen bitkisel ilaçların kişiden kişiye değişen etkiler gösterebileceği ve deneysel çalışmalarla çeşitli karışımların oluşturulabileceği bilgisi, modern tıp dünyasında uygulanan tedavi yaklaşımlarının temelini oluşturmuştur (Özdemir ve Erdal, 2021).

Bitkilerin ürettiği doğal ürünler olan sekonder metabolitler (Terpenler, fenolik bileşikler ve azotlu bileşikler) doğrudan ve dolaylı olarak fitoterapinin kaynağını oluşturmaktadır. Bitkilerin

büyümeleri ve gelişmeleri sırasında çok fazla işlevleri olmayan çok sayıda ve çeşitli organik bileşikler olan sekonder metabolitler, ikincil ürünler veya doğal ürünler olarak da adlandırılırlar (Tiring ve ark., 2021). Daha sonra yapılan çalışmalarda sekonder metabolitlerin bitkilerin zararlılara, hastalıklara, olumsuz çevre koşullarına karşı dayanıklılık oluşturması ve bazı yabancı otlara karşı allelopatik etki göstermesinden dolayı bitkinin yaşamsal işlevi açısından en az birincil metabolitler kadar önemli olduğu tespit edilmiştir.

Sekonder metabolitler canlıların sağlığı üzerinde koruyucu ve destekleyici etkileri nedeniyle günümüzde pek çok endüstride ham madde olarak değerlendirilmektedir. Tıp ve eczacılıkta yaygın kullanım alanı bulmalarının yanı sıra fonksiyonel gıdalar ve besin takviyelerinde de önemli bir yere sahiptirler. İlk kez 1891 yılında tanımlanan bu bileşikler, antiinflamatuar, antioksidan, hipoglisemik ve hipolipidemik etkiler göstermektedir. Ayrıca söz konusu bileşikler tromboz ve kanser gelişimine karşı koruyucu nitelik taşıyabildikleri de ortaya konulmuştur. Bu çok yönlü biyolojik aktiviteler, söz konusu bileşiklerin obezite, diyabet, metabolik sendrom, dislipidemi, kardiyovasküler hastalıklar ve kanser gibi çeşitli kronik hastalıkların önlenmesinde potansiyel bir rol üstlenebileceğini düşündürmektedir (Ülger ve Ayhan, 2020).

3. Hayvan Sağlığı ve Beslenmesinde Fitoterapi

Dünya nüfusunun hızla artmasıyla birlikte gıda talebi de önemli ölçüde yükselmiş, bu ihtiyacı karşılamak amacıyla bitkisel ve hayvansal üretimde çeşitli kimyasal maddelerin ve ilaçların kontrolsüz biçimde daha yoğun kullanılmaya başlandığı görülmüştür. Özellikle antibiyotikler başta olmak üzere birçok kimyasalın gıdalarda bıraktığı kalıntılar, tüketicilerde gıda güvenliği konusunda ciddi endişelere yol açmaktadır. Bu kaygıları azaltmak amacıyla gelişen organik üretim anlayışı, son yıllarda pek çok ülkede organik hayvancılığın hızla yaygınlaşmasına neden olmuştur. Organik hayvancılıkta sentetik veteriner ilaçlarının ve antibiyotiklerin kullanımına yönelik kısıtlamalar, alternatif tedavi seçeneklerinin araştırılmasını zorunlu kılmaktadır. Bu doğrultuda, hem insan hem de hayvan sağlığında hastalıkların önlenmesi ve mevcut semptomların hafifletilmesi amacıyla bitkisel kaynaklı ürünlerin kullanılmasını ifade eden fitoterapi uygulamaları önemli bir seçenek olarak öne çıkmaktadır (Yanar ve Aktaş, 2021; Kaymaz ve Gülümser, 2023).

İkinci bileşikler hem rumen fonksiyonlarının korunması hem de hayvansal üretimde verimliliğin artırılması açısından önemli bir yere sahip olduğu çeşitli araştırmalarda ortaya konmuştur. Söz konusu bileşiklerce zengin bitkilerle beslenen hayvanlarda yem tüketiminin yükseldiği ve bunun da ürün miktarı ile kalitesine olumlu yansıdığı bildirilmektedir. Ayrıca flavonoidler ve fenolik maddeler, belirgin antioksidan ve antimikrobiyal aktiviteleri sayesinde ruminantlarda şişkinlik ve asidoz gibi beslenmeye bağlı sorunların kontrol altına alınmasına katkı sağlamaktadır. Doğal antibiyotiklere duyulan ihtiyacı azaltarak hayvan sağlığı ve verimliliği açısından önemli bir avantaj sunmaktadır. Nitekim 2006 yılında hayvan beslemede antibiyotik kullanımına getirilen kısıtlamalar sonrasında, sekonder metabolit içeren bitkiler doğal antimikrobiyal kaynaklar olarak öne çıkmış ve alternatif bir seçenek hâline gelmiştir (Rochfort ve ark., 2008; Santos Neto ve ark., 2009; Frozza ve ark., 2013; Seradj ve ark., 2014; Paula ve ark., 2016; Patra ve ark., 2016; Lee ve ark., 2017; Kaymaz ve Gülümser, 2023).

4. Fitoterapide Öne Çıkan Bazı Bitkiler

Bitkiler, hastalık ve zararlılara karşı savunma amacıyla işlev gören, aynı zamanda çeşitli fizyolojik süreçlerde sinyal molekülü olarak rol alan geniş bir ikincil bileşikler üretmektedir. Bu bileşikler, sahip oldukları çok yönlü biyolojik ve farmakolojik etkiler nedeniyle dikkat çekmektedir. Nitekim pek çok bitki ya da onlardan elde edilen türevler, geçmişten günümüze enfeksiyonların, sağlık bozukluklarının ve çeşitli hastalıkların tedavisinde doğal bir kaynak

olarak kullanılmaya devam etmektedir. Bitkiler ve bitki özütleri ile yapılan birçok çalışmalarda ikincil bileşiklerin çeşitli hasatlıklara karşı kullanılma imkânlarının değerlendirilmesi amacıyla yürütülmüştür (Meenakshisundaram ve ark., 2016; Da Silva ve ark., 2017; Hajaji ve ark., 2018; Giovanelli ve ark., 2018; Saddiqe ve ark., 2019).

4.1. Aslan dişi (*Taraxacum officinale L.*): Papatyagiller (Asteraceae) familyasından, Avrasya'ya özgü, yenilebilir, otsu, çok yıllık bir yabani çiçek veya ottur. Bitkinin yaygın adı, dişli koyu yeşil yapraklarına atıfta bulunarak "aslan dişi" anlamına gelmektedir. Aslan dişinin kültürel olarak yetiştirilmesi yaygın olmamakla birlikte, geleneksel uygulamalarda kök ve yapraklarının çeşitli amaçlarla kullanıldığı bilinmektedir. Besin içeriği incelendiğinde, özellikle yapraklarının protein, karbonhidrat, kalsiyum, magnezyum ve B grubu vitaminler açısından zengin bir bileşime sahip olduğu görülmektedir.

4.2. Sinir otu (*Plantago* spp.): Plantaginaceae familyasından yaklaşık 200 çiçekli bitki türünü kapsayanbir cins olan sinir otu, yüzyıllardır tıbbi amaçlarla kullanılan bir bitki olup geçmişte köpek ısırıkları, astım ve diş ağrısı gibi çeşitli sağlık sorunlarının tedavisinde yararlanılmıştır. Günümüzde ise en uygun değerlendirme alanının mera karışımları olduğu belirtilmekte; ayrıca bitkinin özellikle kalsiyum ve magnezyum bakımından zengin mineral içeriği ile dikkat çektiği bildirilmektedir.

4.3. Hindiba (*Cichorium intybus L.*): Asteraceae familyasından, genellikle parlak mavi, nadiren beyaz veya pembe çiçeklere sahip, odunsu, çok yıllık bir otsu bitkidir. Avrupa'ya özgü olan bu bitki, Amerika ve Avustralya'ya da getirilmiştir. Hindibanın insan tarafından kullanımı çok eski dönemlere uzanmakta olup, Antik Mısır'da kanı ve karaciğeri arındırdığına ve kalp rahatsızlıklarının tedavisinde yararlı olduğuna inanıldığı bilinmektedir. Çiftlik hayvanları tarafından da iştahla tüketilen bu bitki, daha sonra Yeni Zelanda'da ticari olarak yetiştirilerek piyasaya sunulmuştur.

4.4. Soda otu (*Salsola* spp.): Kazayağıgiller (Chenopodiaceae) familyası içerisindeki "Soda otu" (Salsola) içerisinde yer alan endemik bir türdür. Tuzlu, kurak ve ılıman ekosistemlerde yaygın olarak yetişebilen bu bitkiler, yüksek sıcaklık ve tuzluluk düzeylerinde dahi yüksek tohum ve ot verimi sağlayabilmektedir. Diğer kültür bitkilerinin kuruyarak besin değerini kaybettiği dönemlerde ise yüksek protein içerikleri sayesinde alternatif ve değerli bir yem kaynağı olarak öne çıkmaktadır.

4.5. Çayır düğmesi (Sanguisorba spp.): Gülgiller (Rosaceae) familyasından çok yıllık bir bitki türü olan çayır düğmesinin anavatanı batı, orta ve güney Avrupa olmasına karşın, Kuzeybatı Afrika ve Batı Asya'nın güneybatısında ve en çok da Kuzey Amerika'da doğallaşmış durumdadır. Çayır düğmesinin otu, hayvanlar tarafından iştahla tüketilen, lezzetli ve yüksek besleme değerine sahip bir yem bitkisidir. Yeşil olarak otlatıldığında bile şişkinliğe yol açmaması, sindirilebilirliğinin yüksek olmasını göstermektedir. Her ne kadar bazı bitkilere göre protein içeriği daha düşük olsa da, sindirilebilirliği nedeniyle hayvan beslemesinde tercih edilmesi önerilmektedir.

4.6. Yem pancarı (*Beta vulgaris* var.): Etli ve şişkin kökü için yetiştirilen iki yıllık bir bitkidir. Yem pancarı, kolay sindirilebilmesi, yüksek enerji içeriği ve süt ile et verimini artırıcı etkileri nedeniyle değerli bir yem bitkisi olarak kabul edilmektedir. Yüksek kuru madde verimi sayesinde silaj yapımında da kullanılabilen bu bitki, özellikle süt veriminde belirgin artış sağlamasıyla dikkat çekmektedir.

4.6. Taş yoncaları (*Melilotus* spp): Sarı ve beyaz çiçekli olan taş yoncaları, Fabaceae familyasından baklagiller bitkileridir. Azot sabitleyici özelliğe sahip olan Melilotus albus, değerli bir bal bitkisi olarak kabul edilir, nektar kaynağıdır ve genellikle yem bitkisi olarak yetiştirilir. Taş yoncaları, düşük tanen içeriği sayesinde besin maddelerinin emilimini artırırken, yüksek lif oranı sindirim sisteminin sağlıklı işleyişine katkı sağlar; bu özellikleri ruminant hayvanlar için büyük önem taşımaktadır. Ayrıca yüksek protein, vitamin ve mineral içeriği ile besleyici bir yem kaynağı olan taş yoncası, özellikle süt inekleri ve besi hayvanları için ideal bir tercih olarak öne çıkmaktadır.

4.7. Şerbetçi otu (*Humulus lupulus* L.): Cannabaceae (kendirgiller) familyasından Temmuz-Eylül ayları arasında yeşilimsi-beyaz renkli çiçekler açan, 2–5 m yüksekliğinde, sarılıcı gövdeli, iki evcikli otsu bir bitki türüdür. Şerbetçi otu, içerdiği sekonder metabolitler sayesinde hayvanların büyümesini destekler ve rumende amonyak üretimini inhibe ederek hayvansal kaynaklı sera gazı emisyonlarının azaltılmasına katkıda bulunur. Ayrıca doğal bir antibiyotik işlevi görmesi, dışarıdan sentetik antibiyotik kullanımını sınırlayarak hayvan sağlığı ve üretiminde önemli avantajlar sağlar.

Tablo 1. Farklı bitkilerde belirlenen bazı ikincil bileşikler

Bitki Adı	KT	TFN	TFL	DPPH	TA
Sinir otu (*Plantago* spp.)	1.0-5.0	11.73	9.74	18.27-86	0.1-0.5
Hindiba (*Cichorium intybus* L.)	0.5-1.5	16.2	5.38	20-79	0.1-5.0
Aslandişi (*Taraxacum officinale* L.)	5.0-10.0	40.50	33.58	30-90	1.0-5.0
Soda otu (*Salsola* spp.)	3.0-5.0	10.7	20.00-50.00	27.3-90	0.1-1.0
Çayır düğmesi (*Sanguisorba* spp.)	1.0-3.0	15.00	10.00-30.00	25-90	0.1-4.0
Yem pancarı (*Beta vulgaris*)	0.1-0.5	40.06	30.08	7.79-75	0.01-0.1
Şerbetçi otu (*Humulus lupulus* L.)	1.38-5.42	11.38-43.41	11.87-13.32	15.6-81.7	2.95-3.72
Taş Yoncası (*Melilotus officinalis*)	0.5-1.5	10.00-50.00	20.00-150.00	40-80	0.1-0.5

KT: Kondanse tanen (%); TFN: Toplam fenolik (mg GA g^{-1}); TFL: Toplam flavonoid (mg QE g^{-1}); DPPH: Radikal kovucu aktivite (%); Total alkaloit (%).

Farklı araştırmacılar tarafından yapılan çalışmalarda bazı bitkilerde belirlenen ikincil bileşikler Tablo 1'deverilmiştir (Uyar, 2012; Yıldırım, 2018; Karadağ, 2019; Kaymaz ve Gülümser, 2023). Bitkilere bakıldığında içerikler bakımından varyasyonu geniş olduğu görülmektedir.

5. Sonuç

Fitoterapi, geçmişten günümüze hem insan hem de hayvan sağlığında önemli bir yere sahip olan, doğal ve etkili bir tedavi yaklaşımıdır. Tıbbi bitkilerin içerdiği sekonder metabolitler; antioksidan, antimikrobiyal, antiinflamatuar ve rumen fonksiyonlarını düzenleyici özellikleri sayesinde hayvan besleme ve sağlığında güçlü bir alternatif oluşturmaktadır. Ruminantlarda şişkinlik, asidoz gibi beslenmeye bağlı problemlerin kontrol altına alınmasında, yem tüketiminin iyileştirilmesinde ve hayvansal ürünlerin verim ile kalitesinin artırılmasında fitoterapik bileşiklerin önemli rol oynadığı çeşitli araştırmalarla ortaya konmuştur. Ayrıca bu bileşiklerin doğal antibiyotik olarak işlev görmesi, özellikle antibiyotik kullanımının sınırlandırıldığı modern hayvancılıkta büyük avantaj sağlamaktadır.

Fitoterapik özellikler taşıyan bitkilerin hem yüksek besleme değerleri hem de fizyolojik süreçlere olumlu etkileri, bu bitkilerin hayvan besleme programlarına entegre edilmesini cazip hâle getirmektedir. Özellikle sürdürülebilir hayvancılık, organik üretim ve çevresel etkilerin azaltılması açısından sekonder metabolitlerce zengin bu bitkilerin kullanımının yaygınlaştırılması önem arz etmektedir.

Sonuç olarak, fitoterapi; hayvan sağlığının korunması, verimliliğin artırılması, antibiyotik kullanımının azaltılması ve çevresel sürdürülebilirliğin desteklenmesi açısından modern hayvancılıkta güçlü bir tamamlayıcı unsur olarak öne çıkmaktadır. Bu alanda yapılacak daha kapsamlı ve kontrollü çalışmalar, bitkisel bileşiklerin hayvansal üretimde daha bilinçli ve etkin kullanımına katkı sağlayacaktır.

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KIRSAL KALKINMA DESTEKLEMELERİNİN BİLECİK İLİNDEKİ DURUMU

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ÖZET

Ülkemizde tarım işletmelerin genel anlamda küçük aile işletmeleri şeklinde olması ve bu işletmelerin tarımsal risklerle baş etmede zorluk yaşamaları, üreticilerin gelir dağılımında eşitsizlikleri ortaya çıkarmış ve bu da tarımın desteklenmesini zorunlu hale getirmiştir. Gelişmiş ya da gelişmekte olan birçok ülkede tarım sektörü yıllardır desteklenmektedir. Bu desteklerin çeşidi ve miktarı yıllara göre değişiklik göstermekte olup, tarım kesimindeki gelir dağılımını düzenlemeyi ve bu kesimin refah düzeyini yükseltmeyi amaçlamaktadır. Bu doğrultuda kırsal kalkınma projeleri, tarımla uğraşan kesime yönelik en önemli politikalardan biri olmuştur. Bilecik ilinin son verilere göre nüfusu 228.673 kişi olup, bu nüfusun sadece %15'i kırsalda ikamet etmektedir. Bilecik ili 8 adet ilçeye ve 243 adet köye sahiptir. İlin toplam tarım alanı 125.000 ha iken, ÇKS (Çiftçi Kayıt Sistemi) sistemine kayıtlı çiftçi sayısı 9.000 kişi, HBS (Hayvancılık Bilgi Sistemi) kayıtlı işletme sayısı 4.900 dür. Kırsal Kalkınma Destekleri kapsamında yapılan projeler ile çiftçilere son 20 yılda toplam 1.851 adet projeye 198 milyon TL hibe desteği verilmiştir. Kırsalda yaşayan gençlere teşvik kapsamsında bitkisel ve hayvansal üretim amaçlı projeler ile 385 kişiye istihdam sağlanmıştır. Kırsal kalkınma projelerinin amacı tarımda makineleşmenin artırılarak işgücü maliyetini düşürmek, entansif yetiştiricilikle daha kontrollü bir üretim sağlamak ve yapılan ges projeleriyle yenilenebilir enerji üreterek dışa bağlı enerji ihtiyacını azaltmaktır. Kırsal kalkınma projelerinin diğer bir amacı da eğitim, sağlık ve sosyal alanlar da yatırımlar yaparak köyden kente göçün önüne geçmektir. Bilecik ili de kırsal da çok fazla göç veren iller arasında yer almaktadır. Bu doğrultuda kırsala olan yatırımlar önem taşımaktadır. Bu derleme ile Bilecik ilinde yapılan tarımsal desteklerin kırsal kalkınma üzerindeki etkilerinin ortaya konması amaçlanmaktadır.

Anahtar kelimeler: Bilecik, kırsal kalkınma, tarımsal destekleme, göç.

THE SITUATION OF RURAL DEVELOPMENT SUPPORTS IN BILECIK

ABSTRACT

In our country, the fact that agricultural enterprises are generally small family farms and that these farms have difficulties coping with agricultural risks has led to income inequalities among producers, making it necessary to support agriculture. In many developed and developing countries, the agricultural sector has been supported for many years. The type and amount of these supports vary from year to year and aim to regulate income distribution in the agricultural sector and increase the welfare level of this population. In this context, rural development projects have become one of the most important policies for those engaged in agriculture. According to the latest data, the population of Bilecik is 228.673, of which only 15% reside in rural areas. Bilecik has 8 districts and 243 villages. The total agricultural land of the province is 125.000 hectares, with 9.000 registered farmers in the Farmer Registration System and 4.900 registered enterprises in the Livestock Information System. Within the scope of Rural Development Supports, a total of 1.851 projects have received 198 million TL in grant support over the last twenty years. Through projects promoting plant and animal production, 385 young people living in rural areas have been provided with employment opportunities. The aim of rural development projects is to increase mechanization in agriculture to reduce labor costs, ensure more controlled production through intensive farming, and decrease dependence on external energy sources by producing renewable energy through solar energy projects. Another aim of rural development projects is to prevent rural-to-urban migration by investing in education, health, and social fields. Bilecik Province is among the regions with a high rate of outmigration from rural areas. In this regard, investments in rural regions are of great importance. This review aims to reveal the effects of agricultural support programs on rural development in Bilecik.

Keywords: Bilecik, rural development, agricultural support, migration.

1. Giriş

Kırsal kalkınma, tarımsal üretimin sürdürülebilirliği, gelir dağılımındaki dengesizliklerin azaltılması ve kırsal yaşam kalitesinin yükseltilmesi açısından büyük önem taşır (Özdemir ve Polat, 2019). Kırsal bölgelerde yürütülen kalkınma çalışmaları, modern üretim tekniklerinin yaygınlaşmasını sağlayarak verimliliği artırırken, eğitim, sağlık, ulaşım ve altyapı hizmetlerinin geliştirilmesiyle sosyal refahı güçlendirir. Ayrıca ekonomik faaliyetlerin çeşitlendirilmesi, kırsal nüfusun kentlere göç etme eğilimini azaltır ve bölgesel kalkınma farklarının kapanmasına katkıda bulunur. Çevresel sürdürülebilirliğin desteklenmesi ve doğal kaynakların bilinçli kullanımı da kırsal kalkınmanın temel unsurları arasında yer alır. Bu nedenle kırsal kalkınma, hem toplumun genel refahı hem de ülkenin ekonomik ve sosyal dengesi için stratejik bir önem taşır (Ata ve Dallı, 2024).

Ülkemizde tarım işletmelerinin çoğunlukla küçük ölçekli aile yapısında olması ve bu işletmelerin tarımsal riskler karşısında yeterince dayanıklı olamaması, üreticiler arasında gelir dengesizliklerinin ortaya çıkmasına yol açmıştır. Bu durum, tarım sektörüne yönelik desteklerin kaçınılmaz hâle gelmesine neden olmuştur. Gerek gelişmiş gerekse gelişmekte olan pek çok ülkede tarım sektörü uzun yıllardır çeşitli şekillerde desteklenmektedir. Söz konusu desteklerin türü ve kapsamı zaman içinde değişse de temel amaç, tarımsal gelirlerin daha adil bir şekilde dağılmasını sağlamak ve tarım kesiminin yaşam standartlarını yükseltmektir (Coşkun ve İnan, 2016).

Bilecik, 4.307 km² yüzölçümü ile Türkiye'de iller arasında alan bakımından küçük sayılır. Ekonomi büyük ölçüde tarım ve hayvancılığa dayanır; ilde tarla bitkileri, sebze-meyve üretimi, seracılık, meyvecilik, ipekböcekçiliği, arıcılık ve hayvancılık gibi üretim faaliyetleri yaygındır. Ancak, tarım alanlarının toplam arazi içindeki payı sınırlıdır. Bilecik'te yaklaşık %29'u tarım alanı, % 53'ü orman, %1.4'ü çayır-mera ve geriye kalan kısım yerleşim ya da tarıma elverişsiz arazilerden oluşur (Anonim, 2025a).

Bu derleme ile Bilecik ilinde tarımsal desteklemelerinin kırsal kalkınma üzerindeki etkilerinin ortaya konması planlanmaktadır.

2. Bilecik ilinde gerçekleşen tarımsal desteklemeler

Tablo 1'de Bilecik ilinin son 20 yıldaki tarımsal desteklemeleri verilmiştir. Sayı bakımından makine ekipmanları ilk sırayı alırken, bunu 412 adet proje ile gen çiftçi yatırımları izlemiştir. Diğer taraftan en fazla bütçe 46 milyon ile diğer projeler (Et-süt işleme tesisi, boza üretim tesisi, yumurta paketleme, su ürünleri üretimi işleme ve paketleme tesisi ve meyve sebze paketleme tesisleri) ile 40 milyon ile kümes yapımlarının olduğu görülmektedir. Son dönemlerde dikkat çeken güneş enerji sistemleri (GES) Bilecik ilinde de gitgide popüler bir yatırım haline gelmiştir. Bilecik ilinin tarımsal yelpazesi oldukça geniştir. Örtü altı yetiştiriciliğinin de yoğun olarak yapıldığı ilde, söz konusu tarımsal üretim için 23 adet proje desteklenmemiştir (Anonim, 2025b).

Bilecik ilinde son 20 yılda uygulanan tarımsal desteklemeler, kırsal kalkınmayı hem ekonomik hem de yapısal açıdan önemli ölçüde güçlendirmiştir. Özellikle makine ve ekipman desteklerinin sayı bakımından ilk sırayı alması, üretimde modernizasyonun hızlandığını ve çiftçilerin verimliliklerinin arttığını göstermektedir. Genç çiftçi yatırımlarının 412 proje ile yüksek bir paya sahip olması, genç nüfusun tarımsal faaliyetlerde kalmasını teşvik ederek kırsal alanda istihdamı ve demografik canlılığı desteklemiştir. Et-süt işleme, paketleme tesisleri ve kümes yapıları gibi yüksek bütçeli yatırımlar ise tarımsal katma değer yaratma kapasitesini artırarak yerel ekonominin çeşitlenmesine katkı sağlamıştır. Son yıllarda popülerleşen GES projeleri, kırsal alanda yenilenebilir enerji kullanımını yaygınlaştırarak sürdürülebilir

kalkınmayı desteklemiştir. Örtü altı yetiştiriciliği ve kırsal turizm gibi farklı alanlardaki yatırımlar da Bilecik'in tarımsal yelpazesini genişletmiş, kırsal ekonomiyi çok yönlü hale getirmiştir. Toplamda 1851 projenin 197 milyon TL bütçeyle desteklenmiş olması, bu yatırımların Bilecik'te kırsal kalkınmayı hem ekonomik hem sosyal açıdan önemli ölçüde teşvik ettiğini ortaya koymaktadır.

Tablo 1. 2004-2024 yılları Toplam Proje Durumu

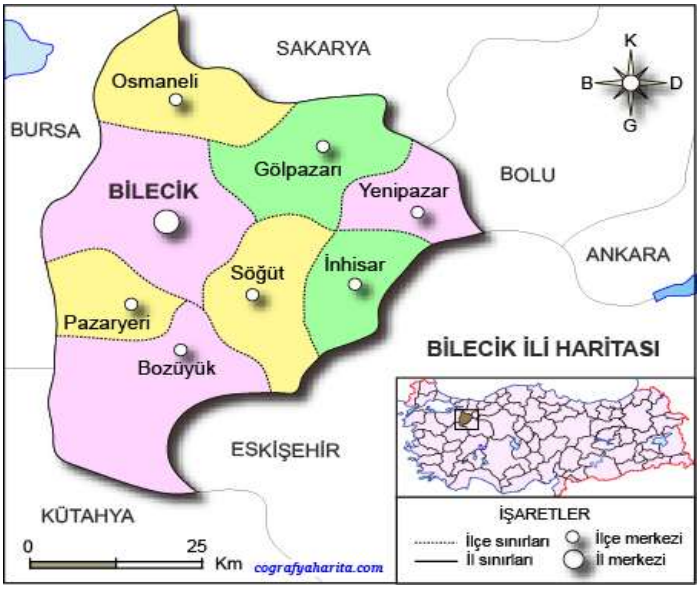
Proje Konusu	**Sayısı**	**Hibe Tutarı**
Kırsal Turizm Kapsamında Otel Projesi	2	2.707.974,69
GES Projeleri	7	19.130.462,53
Ahır-Ağıl Yatırımları	7	18.741.725,27
Örtüaltı Yetiştiriciliği	23	30.721.784,86
Broiler Kümes	21	40.277.568,71
Genç Çiftçi Projeleri	412	12.360.000,00
Makine Ekipman	1.340	27.033.586,58
Diğer Projeler	39	46.977.109,52
Toplam	**1.851**	**197.950.212,16**

3. Bilecik ili nüfusu

Bilecik ilinin toplam nüfusu 2024 yılı sonu itibarıyla **228.495** kişidir. Bu nüfusun yaklaşık %50.56'sı erkek (115.524 kişi), %49.44'ü ise kadın (112.971 kişi) olarak kaydedilmiştir. İl merkezinin nüfusu (merkez ilçe) 2024'te **82.403** kişi olarak açıklanmıştır. İlçe bazında bakarsak; 2024 itibarıyla en kalabalık ilçeleri sırasıyla merkez ile Bozüyük ilçesi (80.865 kişi) izlemektedir (Anonim, 2025a).

4. Bilecik ili tarımsal potansiyeli

Marmara, Karadeniz, İç Anadolu ve Ege Bölgelerinin kesim noktaları üzerinde, dört coğrafi bölgede toprakları olan Türkiye'deki tek ildir. Kuzey Anadolu dağlarının denizden içeriye doğru ikinci serisi olan Köroğlu Dağları ilin topraklarında başladığından arazinin batıdan doğuya doğru birden yükselmesine neden olur. Bozüyük Ovası ve Sakarya ırmağı ile kuzey-güney yönünde iki bölüme ayırır ve dağlar bu ırmağın her iki yakasında devam eder. Bilecik ilinin deniz seviyesinden yüksekliği 500 metredir. İlin en yüksek noktası Bozüyük ilçesinin batı ve güneybatısında yer alan yükseltiler üzerindeki Kala Dağı'dır (1906 m). Genellikle Sakarya Irmağı boyunca uzanan çok geniş olmayan düzlükler şeklinde ovalar il topraklarının % 7'lik bir bölümünü kaplar. Bozüyük, Gölpazarı, Osmaneli ve Pazaryeri Ovaları başlıca düzlük alanlardır. İlde yayla tanımı içerisine sokulabilecek düzlükler çok azdır. Yağış yönünden yeterli miktara sahip olan Bilecik ili, yüzölçümünün %47'sinin ormanlık alan olması nedeniyle hem bitki hem de hayvan bakımından zenginleşmesini sağlamıştır (Anonim, 2025c).



Şekil 1. Bilecik ili ve ilçeleri (Anonim, 2025d)

Bilecik ilinin **yaklaşık % 29.0**'u tarım arazisi, **% 1.4**'ü çayır-mera, **% 53.1** kadarı orman arazisi ve geriye kalanı (yaklaşık %16.5) yerleşim alanı ile tarıma elverişsiz arazi olarak dağılım göstermektedir. Tarım arazilerinin içinde ise tahıl (buğday, arpa, yulaf, vb), yem bitkileri, endüstri bitkileri, sebze ve meyve yetiştiriciliği gibi farklı kategoriler yer almaktadır. Özellikle son yıllarda örtü altı (sera) üretimi, sebze ve meyve bahçeciliği, yağlık ayçiçeği gibi endüstri bitkileri, meyvecilik ve sebzecilik gibi üretim dallarında çeşitlilik vardır. Örneğin, ilde yağlık ayçiçeği ekim alanı 2024 itibarıyla 90.000 dekara ulaşmış; bu alanda dekardan 350 kg'a yaklaşan verim alınmakta; üretim miktarı ve verim artışı ile Bilecik yağlık ayçiçeği üretiminde öne çıkan illerden biri haline gelmiştir.

5. Sonuç

Bilecik ilinde son 20 yılda uygulanan kırsal kalkınma desteklemeleri, hem tarımsal üretimin çeşitliliğini hem de kırsal yaşamın ekonomik gücünü önemli ölçüde artırmıştır. Makine-ekipman yatırımlarından genç çiftçi projelerine, örtü altı yetiştiriciliğinden GES uygulamalarına kadar geniş bir yelpazede sağlanan 1.851 proje ve yaklaşık 198 milyon TL'lik destek, ilde tarımsal modernleşmenin hızlanmasına katkı sağlamıştır. Coğrafi ve ekolojik çeşitliliği ile farklı üretim desenlerine elverişli olan Bilecik, özellikle yağlık ayçiçeği, sebze-meyve yetiştiriciliği ve örtü altı üretimde bölgesel ölçekte rekabet gücünü artırmaktadır. Kırsal turizm ve yenilenebilir enerji yatırımlarının da desteklenmesi, kırsal ekonominin sadece tarım odaklı değil, daha çok yönlü bir yapıya doğru evrildiğini göstermektedir. Genel olarak değerlendirildiğinde, Bilecik ilinde verilen tarımsal desteklerin kırsal kalkınmayı güçlendirdiği, üretici gelirlerini artırdığı ve kırsal alanda sürdürülebilir ekonomik büyüme için önemli fırsatlar sunduğu söylenebilir. Bu kapsamda, mevcut desteklerin niteliğinin geliştirilmesi ve üretici ihtiyaçlarına göre çeşitlendirilmesi, ilin tarımsal potansiyelinin daha etkin şekilde kullanılmasına katkı sağlayacaktır.

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STIMULI-RESPONSIVE NANOPARTICLE-ASSISTED IMMUNOTHERAPY: A NEW WEAPON AGAINST SOLID TUMOURS

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SUMMARY

Solid tumours remain one of the most challenging forms of cancer due to poor drug penetration, immunosuppressive tumour microenvironments, and systemic toxicity associated with conventional therapies. Stimuli-responsive nanoparticles (NPs) enable controlled and targeted drug delivery by responding to internal stimuli, such as pH, enzymes, and redox potential, or external triggers, such as light, heat, and ultrasound. When combined with immunotherapy, NPs enhance cytotoxic T cell activation, improve antigen presentation, and modulate immunosuppressive cells, boosting anti-tumour immune responses. Preclinical studies demonstrate improved therapeutic efficacy and reduced toxicity with NP-assisted immunotherapy (Srivastava et al., 2023). This paper explores NP design, stimuli-responsive mechanisms, synergistic immunotherapy, multifunctional theranostic platforms, challenges, and future directions for clinical translation.

INTRODUCTION

Solid tumours account for the majority of cancer-related deaths worldwide. Conventional chemotherapy and immunotherapy often fail due to limited penetration into the tumour and the immunosuppressive tumour microenvironment. Immunotherapy—including checkpoint inhibitors and adoptive T cell therapies—has significantly advanced cancer treatment; however, its effectiveness against solid tumours is often restricted by poor immune cell infiltration and inadequate antigen presentation (Chen et al., 2022).

Nanotechnology provides innovative solutions for these challenges. Stimuli-responsive nanoparticles (NPs) can release therapeutic payloads selectively at the tumour site. Internal triggers such as acidic pH, elevated enzyme activity, and reactive oxygen species (ROS) levels enable selective activation within the tumour microenvironment. External triggers, such as near-infrared (NIR) light, focused ultrasound, or mild hyperthermia, provide spatiotemporal control over payload release (Wang et al., 2021; Srivastava et al., 2023).

By integrating NP-mediated delivery with immunotherapy, this approach enhances tumour targeting, boosts immune response, and reduces systemic toxicity. This interdisciplinary strategy, bridging materials science, biomedical engineering, and immunology, offers a promising avenue for next-generation cancer treatment.

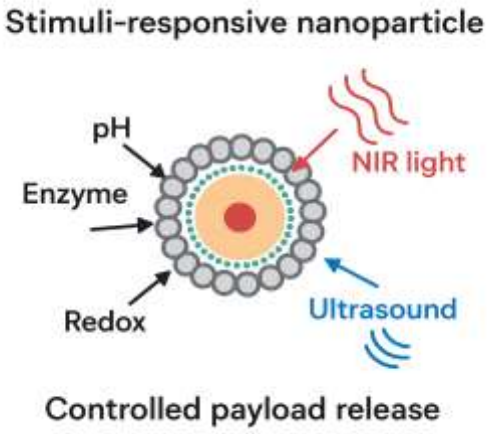

Figure 1: Schematic of Stimuli-Responsive Nanoparticle Mechanisms

Figure 1 illustrates the core mechanisms of stimuli-responsive nanoparticles, including TME-triggered cargo release, improved immune cell infiltration, and enhanced antigen presentation.

RESEARCH AND FINDINGS

Design of Stimuli-Responsive Nanoparticles

Stimuli-responsive NPs are engineered to respond to specific triggers, allowing controlled release at the tumour site.

Internal stimuli include:

- **pH-sensitive NPs:** Degrade in acidic tumour microenvironments.
- **Enzyme-responsive NPs:** Activated by matrix metalloproteinases (MMPs) overexpressed in tumours.
- **Redox-responsive NPs:** Triggered by elevated intracellular ROS levels.

External stimuli include

NIR light, focused ultrasound, magnetic fields, and heat.

NP platforms include lipid-based, polymeric, and inorganic systems:

- **Lipid NPs:** High biocompatibility, prolonged circulation.
- **Polymeric NPs:** Tunable degradation, multifunctional capacity.
- **Inorganic NPs:** (e.g., gold, silica) photothermal therapy and imaging capabilities (Liu et al., 2020; Srivastava et al., 2023).

Table 1. Summary of Preclinical Studies

NP Type	Stimulus	Immunotherapy Combined	Outcome	Reference
Polymeric NP	pH-sensitive	Checkpoint inhibitor	Tumour regression	Wang et al., 2021
Lipid NP	Enzyme-sensitive	T cell therapy	Reduced systemic toxicity	Chen et al., 2022
Gold NP	NIR light	Cytokine delivery	Enhanced T cell infiltration	Liu et al., 2020
RBC Membrane-coated NP	Single-wavelength NIR	Biomarker estimation	Tumour delineation and immune modulation	Srivastava et al., 2023

Mechanisms for Controlled Drug Release

Stimuli-responsive NPs release immunotherapeutic agents selectively at the tumour site. For instance, pH-sensitive polymeric NPs degrade in acidic environments, releasing checkpoint inhibitors directly into tumour tissues. Enzyme-responsive NPs activate in the presence of MMPs. External triggers, such as NIR light, allow on-demand release, providing high spatiotemporal precision and minimizing systemic toxicity (Shi et al., 2017; Srivastava et al., 2023).

Synergy with Immunotherapy

NPs enhance immunotherapy by improving:

- Cytotoxic T cell infiltration
- Antigen presentation
- Reduction of regulatory T cells and myeloid-derived suppressor cells (MDSCs)

Preclinical studies indicate that NP-assisted immunotherapy combined with checkpoint inhibitors or adoptive T cell therapy significantly improves tumour regression and reduces off-target toxicity (Chen et al., 2022; Wang et al., 2021; Srivastava et al., 2023).

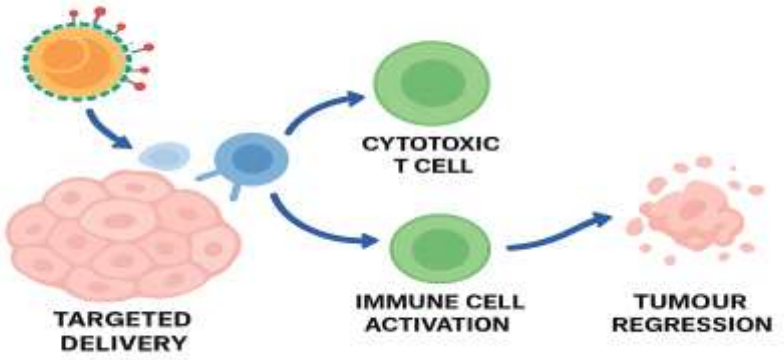

Figure 2 Overview of Nanoparticle–Immune System Interactions

Figure 2 shows major interactions between nanoparticles and the immune system, including dendritic cell activation, antigen cross-presentation, and activation of cytotoxic T lymphocytes (CTLs).

Multifunctionality and Theranostics

Multifunctional NPs integrate therapy and imaging (theranostics). Imaging agents such as fluorescent dyes or MRI contrast agents can be incorporated into the NPs, allowing monitoring of NP distribution and treatment efficacy. Recent studies show that RBC membrane-coated nanoparticles can delineate tumour regions and estimate biomarker expression with a single excitation wavelength, highlighting the versatility of NP platforms for both therapeutic and diagnostic applications (Srivastava et al., 2023).

Challenges and Optimization

Despite promising results, challenges remain:

- Biocompatibility and long-term safety of NPs.
- Tumour heterogeneity, affecting NP penetration and uniformity.
- Stability and shelf-life of NPs.

Optimization strategies include surface functionalization with targeting ligands, size control, and multifunctional design for combined therapy and imaging.

CONCLUSION

Stimuli-responsive nanoparticle-assisted immunotherapy provides a versatile strategy to overcome limitations of conventional solid tumour treatments. By combining nanotechnology with immunotherapy, this approach enables targeted, controlled, and safer therapy while enhancing immune responses. RBC membrane-coated and other functionalized nanoparticles demonstrate potential for combined therapy and real-time diagnostic imaging. Future research should focus on clinical translation, optimizing NP biocompatibility, tumour specificity, and the development of multifunctional theranostic platforms. This interdisciplinary approach bridges engineering and biomedical sciences, paving the way for next-generation cancer therapeutics.

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KEYWORDS: Solid tumour, immunotherapy, stimuli-responsive nanoparticles, drug delivery, tumour microenvironment, RBC membrane-coated nanoparticles

GROWTH PERFORMANCE AND FEED EFFICIENCY OF *CLARIAS GARIEPINUS* FED GRADED LEVELS OF *SESAME INDICUM* (BENI SEED) AS FISH MEAL SUBSTITUTE

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ABSTRACT

This study evaluated the growth performance and feed utilization efficiency of *Clarias gariepinus* fed diets with graded levels of Beni seed meal substituting fish meal. A total of three hundred and sixty (360) *Clarias gariepinus* of the same age, with a size of 5.0±0.20 cm, were stocked in six dietary treatments (DT1 to DT6) with varying levels of Beni seed meal (0% to 100%) and monitored over the experimental period. Feed formulation followed Pearson's square method, maintaining a 40% crude protein level. Data on weight gain, specific growth rate (SGR), feed conversion ratio (FCR), and protein efficiency ratio (PER) were statistically analyzed using ANOVA. Results indicated that diet DT4 (50% Beni seed, 50% fishmeal) yielded the best performance, with the highest final length (25.67±2.5 cm), weight gain (8.47±5.04 g), SGR (1.22±0.18), PER (7.80±0.97), and lowest FCR (3.24±0.40). Complete replacement (DT6) significantly reduced growth and feed utilization, likely due to the presence of anti-nutritional factors. Survival rates were generally high across treatments, with DT4 and DT3 achieving the highest rates (99.00% and 98.67%, respectively). In conclusion, partial substitution of fishmeal with Beni seed meal up to 50–75% significantly enhances growth rate and feed efficiency in *Clarias gariepinus*, making it a sustainable and cost-effective alternative. It is recommended that further studies explore processing techniques (e.g., fermentation) to reduce anti-nutritional factors and evaluate the use of Beni seed meal in other fish species.

Keywords: Growth performance, fish feed, *Clarias gariepinus*, Beni seed, and diets

INTRODUCTION

Fish farming (aquaculture) has also become a valuable source of global food security, needing to offer humanity a stable source of protein (FAO, 2020; Naylor et al., 2000). Catfish (*Clarias gariepinus*) farming is one of the most promising ventures in the aquaculture sector in Nigeria, and this is attributed to their rapid growth and ability to withstand. *Clarias gariepinus* has been identified as among the most popular cultivated freshwater fish in Nigeria, since it can be adapted to suit differing environmental factors, grows fast, and can be reared in an intensive way. It is favored among fish farmers because of its economic significance as a source of income and food security, where it is flourishing in a variety of culture systems throughout the country. Its ability to endure, withstand diseases, and high-feed ratio ensures that its use is preferred in the aquaculture industry in Nigeria, which is playing a critical role in fulfilling the growing demand for fish protein locally and internationally (Olaleye et al., 2024; Olapade and George, 2019). The most conventional protein meal in fish meals and diets is fish meal, which is a necessary source of essential amino acids that enable optimal growth; nevertheless, its high cost and insufficient supply have prompted the search for low-cost and, at the same time, sustainable alternatives (Abdelhedi et al., 2021). As alternatives, partial substitutes have been tested using plant-based sources of protein like the soybean meal and sunflower meal, which are readily available and contain reasonably good protein content. Research indicates that substitution of fish meal with these vegetable proteins, which usually contain synthetic amino acids, may sustain or even improve growth performance, feed consumption, and health condition of *C. gariepinus* in a way that there is no negative effect on liver and kidney functions (Abdelhedi et al., 2021; Adeyemo et al., 2024). However, the most common plant-based source of protein utilized in the composition of fish meal is soybean (Adesina, 2017; Ndatsu et al., 2022). Nature has excess plants, which may be used as a source of plant-based protein that would substitute soybeans, which are economical and easily accessible, and thus help reduce the price of fish meal (Adesina, 2017; Ndatsu et al., 2022). Beni seed (*Sesamum indicum*) is a Pedaliaceae species that is prevalent in Asian and African nations (Dossa et al., 2023; Garbia et al., 2000). But it is generally referred to as Beniseed in Nigeria. The small, round grain is consumable and tastes like milk and flowers. The oil is also used in cooking and to make margarine and pharmaceuticals. Beni seed oil has also been reported to have the antioxidant beta-carotene and steroids (Wei et al., 2022). A report by Njoku et al. (2010) indicates that *Sesame indicum* seed oil and oil extracts have practical applications as nutritional supplements in animal diets. It is a significant oil resource, which was deemed to have originated in tropical Africa, where the rank of diversity is the most incredible (Raw Materials Research and Development Council [RMRDC], 2004). The seed is eaten fresh, dried, or fried, or mixed with sugar. As a paste, it is also used in certain local soups. Beni seed has been extensively utilized as a protein supplement in fish diets because of its good nutritional composition in terms of digestibility, growth, and use of the feed in domestic animals (Madina and Agbaji, 2021; Otuu and Obeta, 2024). According to Yakubu et al. (2020), Beni seed meal supplementation of *Clarias gariepinus* diets showed an excellent effect on growth parameters, such as weight gain, specific growth rate, protein efficiency ratio, feed intake, and survival rate. Due to its decreasing supply and increasing price, fish meal has created significant problems in the aquaculture sector since it is an essential ingredient of food demand (FAO, 2023). As a result, alternative sources of protein, which are affordable, sustainable, and nutritionally competent to be added to aquafeed, are urgently required (Serra et al., 2024). Although Beni seed meal has potential as a fish meal alternative, other species have not been studied extensively (Yakubu et al., 2022). Thus, the purpose of this study is to assess growth performance and feed utilization of *Clarias gariepinus* at graded levels of Beni seed meal that replaces fishmeal in the diets of African mud catfish.

2. MATERIALS AND METHODS

The diet was formulated using beniseed (white cultivar), fishmeal, groundnut cake, and maize bought at Lapai market. Then, healthy *Clarias gariepinus* were purchased at White Light Fish Farm and General Enterprise, along Lapai-Agaie in Niger State.

Sample preparation

Sample processing was done in the Department of Biochemistry laboratory at Ibrahim Badamasi Babangida University, Lapai, Niger State. The white cultivar of Beni seed (*Sesame indicum*) was used for the experiment. The feed ingredients were first sun-dried to constant weight, and then they were subjected to milling to decrease the moisture content. The ingredients were then ground separately in a RICHI SFSP56×40 feed hammer mill (China) that was equipped with a 1.0 mm mesh size, ensuring that all materials were ground to a consistent particle size. The ground ingredients were weighed in the desired proportions for each diet. The amount of each ingredient was determined with a sensitive weighing balance (TH-2000, Hangzhou Gongheng Weighing Equipment Co., Ltd., China). Once the ingredients were mixed thoroughly, cassava starch was introduced as a binding agent to help keep the feed together. The incorporation of hot water resulted in the production of dough for pelleting with a pelleting machine (Hobart A-2007, Hobart LTD, London) that was equipped with a 2 mm die mincer. The dried pellets were then packaged and stored until use.

Stocking and acclimatization of experimental Fish

A total of three hundred sixty (360) *Clarias gariepinus* (African mud catfish) of the same age, with a size of 5.0±0.20 cm, were culled and bought from White Light Fish Farm and General Enterprise, which is situated along the Lapai-Agaie road in Niger State. The fish were carried in aerated containers early in the morning (6:00 am-7:00 am) to the Animal House at Ibrahim Badamasi Babangida University, Lapai, Niger State. They underwent a 2-week acclimatization period and were fed commercial feed twice daily at a rate of 3% of their body weight. Fish were starved for 24 hours before the feeding trial commenced. The length and weight of the fish were recorded as the initial measurements. The water quality parameters, such as temperature, pH, and dissolved oxygen, were continuously monitored, and the water in each tank was replaced when there was a considerable buildup of residual feed and feces as a fish health maintenance measure. The range of water temperature was between 25.00 and 34.00°C, pH varied from 6.00 to 9.2, and the oxygen demand was between 4.00 and 6.10 mg/l.

Feed Formulation and Experimental Design

A total of six diets containing 40% crude protein were designed with the help of the Pearson square method following the NRC (1993) guidelines. They were adjusted according to the methods of Yakubu et al. (2020) and Taheri Mirghaed et al. (2022). A total of six experimental diets consisting of different percentages of Beni (sesame) seed and soybean were made, and the labels were given 1, 2, 3, 4, 5, and 6. The control diet (commercial diet) was represented by Diet 1. Diet 2 contained 0% Beni seed meal and 100% soybean meal, while Diet 3 had 25% Beni seed meal and 75% soybean meal. Diet 5 was composed of 75% Beni seed meal and 25% soybean meal, and Diet 6 consisted of 100% Beni seed meal and no soybean meal.

Experimental Treatment and Design

The experiment consisted of a total of eighteen (18) transparent plastic tanks (60 x 30 x 30 cm), six dietary treatments with three replicates each. Each tank contained 20 fish and was protected by a net to avoid predators. The trial lasted for 12 weeks (90 days), during which fish were fed

the formulated diet at 5% body weight daily (Kumar et al., 2011; Nisarat et al., 2021; Antony et al., 2022).

Sampling of Fish

Fish were sampled every two (2) weeks. Standard length, total length, and weight were determined using a weighing balance and a measuring board. Mortality was also observed and recorded each time a dead fish was found, and the fish was then taken out of the tank.

Growth Performance

Length gain of the fish

This was calculated using the Roberson *et al.* (2000) formula as:

$$\text{Gain in length (cm)} = \text{Mean final length (cm)} - \text{mean initial length(cm)}$$

This was calculated using the Roberson *et al.* (2000) formula as:

$$\text{Weight gain (g)} = \text{Mean final weight (g)} - \text{Mean initial weight (g)}$$

Nutrient Utilization

Specific Growth Rate (SGR)

The SGR for each treatment group of the study was estimated using the formula of Effiong *et al.* (2019) as:

$$SGR = \frac{\ln MFW - \ln MIW}{T2 - T1} \times 100$$

Where T1 = time (days) at stocking, T2 = final time (days) at catch,

LnMFW-lnMIW is the difference between the natural logarithm of MFW and MIW

Food conversion ratio (FCR)

$$\text{The FRC was estimated as (FCR)} = \frac{\text{Total Feed Give}}{\text{Total Weight Gain}}$$

The food conversion ratio expresses the rate at which fish convert the food consumed into weight gain (Effiong *et al.*, 2019).

Protein efficiency ratio (PER)

The protein fed to each fish was estimated as the total feed given multiplied by the feed's crude protein percentage.

$$\text{PER was estimated as (PER)} = \frac{\text{Total weight gain of fish}}{\text{Total protein fed of fish}}$$

Survival rate (%)

The number of fish harvested from each treatment at the end of the experiment, along with the initial data collected, was used to calculate the fish's survival rate. The survival rate was determined using the formula of Roberson *et al.* (2000):

$$\text{Survival rate (SR)} = \frac{\text{Number of harvested fishes}}{} \times 100$$

Statistical analysis

The collected data were subjected to one-way Analysis of Variance (ANOVA) and expressed as mean ± SD to test for differences in diet at $p<0.05$ (Zar, 2010). A post-hoc test (Tukey test) was used to rank the differences in means. Statistical Package for Social Sciences (SPSS) version 27 was used as a statistical tool.

3. RESULTS

Growth Performance of Clarias *gariepinus* fed graded levels of Beni seed diets

Table 4.1 indicates the growth response of *Clarias gariepinus* fed experimental diets with graded concentrations of beniseed meal (*Sesame indicum*) as a substitute for fish meal. Diets DT1, DT2, DT3, and DT6 exhibited a lower insignificant difference value of mean length gain (MLG) as 3.86±1.10, 3.40±1.21, 3.07±0.99, and 3.80±1.20 cm, respectively, compared to diets DT4 and DT5, 5.74±1.2 cm and 5.11±1.60 cm. Furthermore, a significantly higher mean weight gain (MWG) was observed in the treatment diets (DT4 and DT5) at 8.47±5.04 and 8.04±5.22 g, respectively, compared to the other diets (DT1, DT2, DT3, and DT6) (Table 4.2).

Table 1: Growth Performance of *Clarias gariepinus* fed graded levels of Beni seed diets

DIETS	IL (cm)	FL (cm)	MLG (cm)	IW(g)	FW(g)	MWG(g)
DT1	19.47±1.62^{a}	23.33±2.3^{a}	3.86±1.10^{a}	6.27±1.58^{a}	11.40±4.30^{a}	4.13±3.28^{a}
DT2	19.93±0.81^{a}	23.33±0.5^{a}	3.40±1.21^{a}	6.77±0.85^{a}	11.20±3.08^{a}	4.43±3.54^{a}
DT3	19.93±0.81^{a}	23.00±1.7^{a}	3.07±0.99^{a}	6.23±2.44^{a}	11.73±0.25^{a}	4.50±2.66^{a}
DT4	19.93±0.81^{a}	25.67±2.5^{b}	5.74±1.2^{b}	6.93±0.93^{a}	15.40±4.98^{b}	8.47±5.04^{c}
DT5	19.89±0.69^{a}	25.00±0.5^{b}	5.11±1.60^{b}	6.63±1.06^{a}	14.67±3.71^{b}	8.04±5.22^{c}
DT6	19.17±1.50^{a}	23.27±0.5^{b}	3.80±1.20^{a}	6.73±2.84^{a}	11.50±6.21^{a}	5.77±4.48^{b}

Data are shown as mean ± SD of three replicates. Means with different superscript letters in each column are significantly different ($p<0.05$). IL: initial length, FL: final length, MLG: mean

length gain, IW: initial weight, FW: final weight, MWG: mean weight gain, DT refers to diets, and DT1 is the commercial diet. DT2 is formulated with 0% Beni seed meal and 100% soybean meal, DT3 is formulated with 25% Beni meal and 75% soybean meal, DT4 contains 50% Beni seed meal, and 50% soybean meal, DT5 is composed of 75% Beni seed meal and 25% soybean meal, DT6 is 100% Beni seed meal and 0% soybean meal.

Feeding Utilization of *Clarias gariepinus* Fed Graded Levels of Beni Seed Diets.

Table 2 shows the feed utilization efficiency of *Clarias gariepinus* fed experimental rations containing various concentrations of Beni seed as a fish meal substitute. There were significant differences ($p < 0.05$) between the control (DT1) and other treatment groups. Specific growth rate (SGR) was significantly greater in fish fed on DT4 and DT5 diets (1.22±0.18 and 1.01±0.43) when compared to fish fed the other diets. The feed conversion ratio, however, was greater in fish fed diets DT1-DT3 (5.88±1.31, 6.86±3.80, and 5.06±0.71) when compared to fish fed diets DT4 and DT5. Tab. 2. Nevertheless, there was no statistically significant difference in survival rate (SR) between fish fed on all diets, except for fish fed on the control diet (DT1), whose SR was (84.67±4.16).

Table 2: Feeding Utilization of *Clarias gariepinus* fed graded levels of Beni seed diets.

DIETS (%)	SGR	FCR	PER	SR
DT1	0.80 ± 0.13^{a}	5.88 ± 1.31^{a}	2.38 ± 0.88^{a}	84.67 ± 4.16^{a}
DT2	0.57 ± 0.36^{a}	6.86 ± 3.80^{a}	3.98 ± 2.78^{a}	93.33 ± 3.51^{b}
DT3	0.70 ± 0.42^{a}	5.06 ± 0.71^{a}	4.16 ± 2.55^{b}	98.67 ± 1.53^{c}
DT4	1.22 ± 0.18^{b}	3.24 ± 0.40^{b}	7.80 ± 0.97^{c}	99.00 ± 1.00^{c}
DT5	1.01 ± 0.43^{b}	4.00 ± 1.70^{b}	7.11 ± 3.15^{c}	94.33 ± 3.79^{b}
DT6	0.56 ± 0.28^{a}	5.06 ± 6.96^{a}	3.81 ± 2.09^{a}	93.00 ± 2.45^{b}

Data are shown as mean ± SD of three replicates. Means with different superscript letters in each column are significantly different ($p<0.05$). DT refers to diets, SGR: specific growth rate, FCR: feed conversion rate, PER: protein efficiency ratio, SR: survival rate, and DT1 is the commercial diet. DT2 is formulated with 0% Beni seed meal and 100% soybean meal, DT3 is formulated with 25% Beni meal and 75% soybean meal, DT4 contains 50% Beni seed meal, and 50% soybean meal, DT5 is composed of 75% Beni seed meal and 25% soybean meal, DT6 is 100% Beni seed meal and 0% soybean meal.

5. DISCUSSION

In any culture system, the growth response of fish indicates how fish respond to feed, whereby they grow in size (Ndatsu et al., 2020). This may mean that the treated fish are using the experimental diets to grow; this is evidenced by the insignificance of the recorded differences in final length, mean length gained, final weight, and mean weight gained when fish are exposed to diets containing DT4 and DT5. Also, there is a possibility that the experimental fish used S. Indicum seed meal, with different percentage ratios, and it was effective, leading to good weight and length gain. This growth may be caused by better absorption of nutrients. There was a significant difference ($p < 0.05$) in initial weight and length among the experimental fish in the

dietary groups, indicating that fish with similar weights in the same stock or age group had different lengths. The ability of Beni seed meal and soybean meals to combine to create an optimal blend of amino acids and fatty acids could also be the cause of the highest growth performance reported in fish fed the diets DT4 and DT5. This is in line with the results of Adebayo and Quadri (2005), who affirm that well-balanced diets of plant protein can be similar to those made of fishmeal. This has been confirmed by recent studies, which indicate that the addition of fishmeal, partially with other plant proteins such as Beni seed meal, can improve the growth of fish in proper proportions (Hussain et al., 2025). Adewolu et al. (2023) suggest that adding up to 50% of alternative plant-based meals to the feeding of *Clarias gariepinus* enhanced the growth parameters and did not affect health. According to Yakubu et al. (2020), Beni seed meal is rich in essential fatty acids and proteins that have the potential to improve the growth of fish. The weight gain indicates that a 50% substitution is an appropriate ratio of the nutrients, though it comes with the cost of poor digestibility. Nevertheless, this decreased growth performance at the levels of DT1, DT2, DT3, and DT6 might be linked to the partial replacement of fish meal at this graded level, which resulted in an unbalanced protein profile that could have influenced the growth performance. The result is in line with the study that has been carried out by Eyo et al. (2020), who propose that a gradual replacement of fish meal with plant-based protein sources needs to be implemented gradually to prevent anti-nutritional factors that may have an influence on digestion. The reduced growth performance in DT6 indicates that a total replacement of fish meal with Beni seed meal may not provide all the essential amino acids for growth. The presence of anti-nutritional compounds, including phytic acid and tannins, which occur at high levels in Beni seed meal, might harm digestibility (Samtiya et al., 2020). The fiber content of Beni seed might also inhibit nutrient absorption, resulting in a decreased growth rate.

Additionally, the utilization of feed by fish within the culture system is also determined by the measurement of important parameters in feed trials. These parameters are specific growth rate (SGR), feed conversion ratio (FCR), protein efficiency ratio (PER), and survival rate (SR), among others. SGR is a term employed in aquaculture to calculate fish production in a given timeframe (Enyidi, 2014; Ndatsu et al., 2022). The increased levels of SGR, which indicated an insignificant difference in fish fed diets (DT4 and DT5), suggest that diets (DT4 and DT5) prepared with different proportions of inclusion percentages of Beni seeds enhanced the growth performance. The observed specific growth rate (SGR) was lower in comparison to values presented in the study of Enyidi (2014) and Fagbero (2000), who recorded considerably higher growth rates. The lowest SGR of the fish-fed diet DT6 is probably due to reduced growth, which may slow down the production rates. One of the key performance indicators (KPI) is a feed conversion ratio (FCR): the ratio of feed measured in kilograms per kilogram of feed consumed to produce a kilogram of fish, and the lower the ratio, the better the feed meal and the feed efficiency. These findings have been supported by the recent investigations that show the fact that reducing FCR diets will lead to better use of nutrients and growth production. It has been established that more positive growth traits are correlated with low values of FCR, and this confirms the efficiency of the feed utilization in aquaculture species (Shi et al., 2024). Furthermore, systematic reviews and meta-analyses have determined that with proper nutritional balance, the replacement of fish meal by plant-protein sources can sustain and even enhance the growth, feed ratio, and the whole health of fish (Hussain et al., 2025; Ahmed et al., 2024). These studies indicate that the optimized plant-protein diets can produce the same results as the traditional fishmeal diets, and this fact supports the application of sustainable and economic aquaculture. The diets of DT4 and DT5 were not significantly differentiated ($p < 0.05$) in the values of FCR but were differentiated significantly compared to other dietary treatments, which means the conversion of this diet toward product is efficient. This could be

the reason why the increase in body weight was high when feeding the fish with DT4 and DT5 was carried out earlier in this study. In addition, the weight gain/protein intake ratio is the weight gain/protein intake. This means that the protein, which is absorbed, may be used completely during growth or an increase in weight. The fact that there is an optimal range of protein use might explain the fact that there is an increase in the value of PER of fish fed diets (DT4 and DT5), which, however, does not differ significantly ($p < 0.05$) from values of the fish fed diets with other dietary treatments. Digestibility and palatability: As Olukunle and Onuegbu (2023) observed, the parameters of digestibility and palatability greatly influence fish feeding with DT Survival Rate (SR), which prevents the negative views of low efficiency of fish fed with DT Survival Rate against available feed in a growth response study. It is employed in order to determine the level of success in any production. It is also required in the establishment of this parameter in feeding trials, as it is the one that is used in establishing the safe level of inclusion of ingredients in formulating the feeds. It prevents increased mortality because there was a higher survival of fish in the experimental diet compared to the control. This may have been attributed to the fact that ammonia content was lower and the stress of the experimental diet was less than that of the control group. This observation falls in line with that of Idowu and Afolayan (2013), though it is not consistent with that of Olapade and George (2019).

Conclusion

Conclusion: This research showed that different proportions of Beni seed (*S. indicum*)-based meal as an alternative to fish meal in *C. gariepinus* diets could be used to increase the growth, feed efficiency, and health and well-being of the fish. The total replacement, however, can lead to nutritional deficiencies, stress, and a slow growth rate because of anti-nutritional factors, and in addition to this, may cause the health and well-being of the fish to degrade. In addition to that, substituting the meal feed of *C. gariepinus* with Beniseed meal may be an economically and nutritionally feasible way of raising a sustainable and economical feed to optimize fish growth. On these results, it might be concluded that the formulated diets (DT4 and DT5) with the inclusion of Beni seeds at 50 percent and 75 percent, respectively. Thus, diets (DT4 and DT5) can emerge to be even more promising than the rest of the diets as they positively impact sufficient growth performance and nutrient use in *C. gariepinus* and can be adopted to create products of different food industries.

Conflict of interest

The authors state that there is no conflict of interest in the article.

Acknowledgments

The authors would also like to acknowledge the guidance and contribution of Dr. Ndatsu Yakubu of the Biochemistry Department and Dr. Mohammed Isah Chado of the Department of Biological Science of Ibrahim Badamasi Babangida University, Lapai, Niger State, to the success of this research study.

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ÇOK PARAMETRELİ AKIŞKAN ÖLÇÜMLERİ İÇİN DENEYSEL TEST DÜZENEĞİ TASARIMI VE ANALİZİ

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ÖZET

Bir akışkan sisteminin performansını belirleyen temel etmenler; sıcaklık, basınç, debi ve basınç yüksekliğidir. Tasarım sürecinde bu parametrelerin dikkate alınması, hedeflenen sistem veriminin sağlanması açısından büyük önem taşır. Bu nedenle, söz konusu değişkenlerin birbirleriyle olan etkileşimlerinin doğru biçimde analiz edilmesi gereklidir. Bu çalışmada, bu dört parametre arasındaki ilişkiyi incelemek amacıyla modüler bir deney düzeneği tasarlanmıştır. Düzenek; akışkana gerekli basıncı sağlayan santrifüj pompa, sıcaklık değişimi için ısıtıcı, debi ölçümü için hacimsel debimetre ve seviye kontrolü için dereceli tanktan oluşmaktadır. Pompa, üç fazlı bir elektrik motoru ile çalıştırılarak sistem basıncının ayarlanabilir olması sağlanmıştır. Tasarım süreci, pompa seçimi ve basınç hesaplarıyla başlatılmış; 0,5 Hp gücünde bir santrifüj pompa tercih edilmiştir. Akış hızı ve debimetre değerleri doğrultusunda boru çapları belirlenmiş, sürtünme kayıpları Darcy–Weisbach denklemiyle hesaplanmıştır. Bu kapsamda borulardaki basınç kaybı 100–200 Pa/m olarak bulunmuş ve DN20 boru tipi seçilmiştir. Farklı akışkanların sıcaklık değişimleriyle test edilebilmesi için 2 kW gücünde bir ısı eşanjörü kullanılmıştır. Elektronik kontrol sistemi için pano tasarımı yapılmış, sistem bileşenleri ağırlık dağılımına göre yerleştirilmiş ve şasi sonlu elemanlar yöntemi (SEY) ile analiz edilmiştir. Von Mises kriterine göre yapılan değerlendirmede şasinin maksimum gerilmesi 6.6 MPa, maksimum yer değiştirmesi ise 0.239 mm olarak hesaplanmıştır. Çalışma, eğitim ve endüstriyel uygulamalarda kullanılabilecek düşük maliyetli, modüler bir test sisteminin geliştirilmesine katkı sağlamaktadır.

Anahtar Kelimeler: Akışkan sistemi, deney düzeneği tasarımı, sonlu elemanlar analizi

DESIGN AND ANALYSIS OF AN EXPERIMENTAL TEST SETUP FOR MULTI-PARAMETER FLUID MEASUREMENTS

ABSTRACT

Temperature, pressure, flow rate, and head are the main parameters that determine the performance of a fluid system. Considering these parameters during the design phase is crucial to achieve the targeted efficiency. Therefore, understanding the interactions among these variables is essential for accurate system analysis. In this study, a modular experimental setup was designed to examine the relationships between these four parameters. The setup consists of a centrifugal pump to provide system pressure, a heater to control fluid temperature, a volumetric flow meter to measure flow rate, and a graduated tank to monitor fluid level. The pump is driven by a three-phase electric motor, allowing adjustable system pressure. The design process began with the selection of the pump and pressure calculations, resulting in the choice of a 0.5 Hp centrifugal pump. Pipe diameters were determined based on the flow rate and flow meter values, while friction losses were calculated using the Darcy–Weisbach equation. The pressure loss in the pipes was found to be between 100–200 Pa/m, and DN20 pipes were selected accordingly. To enable testing with different fluids and temperature variations, a 2 kW heat exchanger was integrated into the system. An electrical control panel was designed, and the components were placed according to weight distribution. The chassis was analyzed using the Finite Element Method (FEM) and evaluated based on the Von Mises criterion. The maximum stress on the chassis was calculated as 6.6 MPa, and the maximum displacement was 0.239 mm. The results indicate that the developed setup provides a low-cost, modular testing system suitable for both educational and industrial applications.

Keywords: Fluid system, experimental setup design, finite element analysis

1.GİRİŞ

Akışkan sistemlerinde sıcaklık, basınç, debi ve seviye; proses mühendisliğinin temel kontrol parametreleri arasında yer almaktadır. Bu değişkenlerin farklı sensör ve düzenekler ile ayrı ayrı ölçülmesi hem zaman hem maliyet açısından verimsiz olmakta, ayrıca senkronizasyon hataları nedeniyle ölçüm doğruluğunu düşürebilmektedir. Bu doğrultuda hazırlanan çalışmanın amacı, söz konusu dört parametrenin tek bir deney düzeneği üzerinde entegre halde ölçülebildiği ve kontrol edilebildiği bir sistem tasarlamaktır.

Analog göstergeler, tüm parametrelerin eş zamanlı olarak izlenmesine imkân tanımakta ve çok değişkenli akış karakteristiğinin gözlemlenebilmesini sağlamaktadır. Bu özellikleriyle düzenek hem laboratuvar temelli eğitim uygulamalarında hem de endüstriyel prototip ve ön tasarım çalışmalarında kullanılmaya uygun, taşınabilir ve düşük maliyetli bir test altyapısı sunmaktadır.

Literatürde akışkan değişkenlerinin ölçümü ve kontrolü üzerine kapsamlı araştırmalar bulunmakla birlikte çoğu çalışma parametreleri bağımsız sistemlerde ele almaktadır. Juan J. Gude Prego ve ark. (2003), çok değişkenli kontrol sistemlerinin klasik tek değişkenli modellere göre daha yüksek operasyonel doğruluk sağladığını belirtmiştir. Atkinson (2009), yoğunluk tabakalaşmasının basınç üzerindeki etkilerini incelemiş ve hidrostatik-dinamik akış farklarına ilişkin hesap yöntemleri geliştirmiştir. Stefan Knaust ve ekibi (2015), süper kritik CO_2 akışkanlarında sıcaklık ve basınç değişimlerinin viskozite ve yoğunluk üzerindeki etkisini ortaya koymuştur. Al-Mufadi (2021) ise nanokompozit silikon kauçuk debi sensörlerinin düşük akış hızlarında daha hassas performans sunduğunu göstermiştir.

Bu çalışmalar birlikte değerlendirildiğinde, dört temel parametrenin tek sistem altında bütünleşik olarak izlenmesine yönelik uygulamaların sınırlı olduğu görülmektedir. Bu çalışma geliştirilen deney düzeneği ile literatürdeki eksikliği gidermeyi ve sıcaklık–basınç–debi–seviye ölçümlerinin aynı platformda gerçekleştirilmesine imkân tanımayı amaçlamaktadır. Böylece çoklu akışkan parametrelerinin eş zamanlı takibi sağlanmakta; deneysel doğruluk ve sistem verimliliği artırılmaktadır.

2. MATERYAL METOT

Bu çalışmada, akışkanların sıcaklık, basınç, akış hızı ve seviye parametreleri sürekli olarak kontrol edilir ve ölçüm değerleri kaydedilir. Parametreler arasındaki etkileşimler sistematik bir şekilde analiz edilir ve çok değişkenli ilişkiler incelenir. Önerilen yöntem, atık su sistemlerinde yaygın olarak kullanılan geleneksel pH kontrol yaklaşımlarından farklı olarak, basınç ve seviye gibi değişkenlerin aynı deneysel düzeneğe entegre edilerek yönetilmesini mümkün kılar (Juan J. Gude Prego, 2003).

Kurulan düzenek, akışkanın sürekli sirkülasyonunu sağlayan kapalı devre hidrolik bir yapıya sahiptir. Sistemde akışın sağlanması için 0.5 Hp gücünde santrifüj pompa kullanılmıştır. Sıcaklık kontrolü, ısıtıcı ve ısı eşanjörü içeren termal devre üzerinden gerçekleştirilmiş; seviye ve basınç kontrolü ise hat üzerine yerleştirilen valfler aracılığıyla sağlanmıştır. Ölçüm ünitesi 6 L hacmindeki dereceli tanka bağlanmıştır ve kullanılan sensörler:

- Debi sensörü: 60 L/dk
- Sıcaklık sensörü: 120°C ölçüm sınırı
- Basınç sensörü: 0–0,6 MPa çalışma aralığı

2.1 POMPA SEÇİMİ

Deneysel düzeneğin hidrolik gereksinimlerini karşılamak üzere seçilmiş santrifüj pompanın performansı, sisteme aktarılan hidrolik güç ve pompa verimliliği üzerinden değerlendirilmektedir. Yapılan bu değerlendirme, seçilen pompanın teknik spefisifikasyonlarının sistem ihtiyaçlarına ne ölçüde cevap verdiğini belirlemek açısından kritik bir öneme sahip olacaktır.

Pompanın akışkana sağladığı Hidrolik Güç ($P_{hidrolik}$) akışkan yoğunluğu(ρ), yerçekimi ivmesi (g), debi (Q) ve toplam basma yüksekliği (H) parametrelerine bağlı olarak aşağıda gösterilen temel hidrolik denklem ile hesaplanmaktadır:

$$P_{hidrolik} = \rho g Q H$$

Pompanın enerji dönüşüm etkinliğini göstermekte olan verimlilik (η) ise, hidrolik güç ($P_{hidrolik}$) ile pompaya sağlanmakta olan elektriksel giriş gücü ($P_{elektrik}$) arasındaki oran kullanılarak tespit edilmektedir. Verimliliğin belirlenmesi, sistemin enerji tüketim profilini ortaya koymak için mutlak bir metriktir.

$$\eta = \frac{P_{hidrolik}}{P_{elektrik}}$$

Bu tip teorik denklemler, pompanın sistem tasarım noktasındaki performansını belirlemek ve seçilen 0.5 HP'lik nominal gücün hidrolik gereksinimleri ne kadar karşıladığını göstermek amacıyla kullanılacaktır.

2.2 ISITMA DEVRESİ

Deneysel platformun termal değişkenini idare etmek için özel olarak tasarlanmış bir ısıtma devresi kurgulanmıştır. Sıcaklık kontrolü, akışkana ısı enerjisi transfer eden tank içerisine monte edilmiş radyatör tipi ısı transfer ünitesi ve bu ünitenin ana güç kaynağı olan 2 kW gücünde bir elektrikli ısıtıcı aracılığıyla gerçekleştirilmiştir. Sistemin akışkan sirkülasyon gereksinimleri, 220V/50 Hz tek fazlı besleme hattına bağlı bir sirkülasyon pompası ile sağlanmaktadır; bu güçsel seçim, laboratuvar standartlarına uygun enerji yönetimini ve güvenilir çalışmayı hedeflemektedir.

Kurulan devre sistemi, akışkan sıcaklığının kontrollü bir şekilde 0˚ ile 120˚ gibi bir aralıkta ayarlanmasına olanak tanımaktadır. Bu aralık, su ve cıva gibi farklı termal karakteristiklere sahip akışkanların test edilmesine imkân tanımak üzere tasarlanmıştır. Ölçüm hassasiyetini temin etmek için, hattın kritik noktasına direkt entegre edilen boru içi termometre vasıtasıyla ölçüm sağlanmıştır. Bu direkt ölçüm metodu, proses boyunca termal karakteristiklerin eş zamanlı gözlemlenmesine ve operatör tarafından hızlı aksiyon alınmasına imkan tanımaktadır.

Isıtma devresinde kullanılan ısıtıcının tasarımı ve güç seçimi, sistemin termal enerji dengesi analizi ile doğrulanmaktadır. Bu analiz, deneysel süreçte hedeflenen sıcaklık değişimlerinin sağlanıp sağlanamayacağını gösterir. Analizde kullanılacak referans akışkanın özgül ısısı (c_p) dikkate alınarak, ısıtıcının gücü ($\dot{Q}_{ısıtıcı}$) ile akışkanın taşıdığı termal enerji arasındaki ilişki aşağıdaki temel denklem ile formüle edilmektedir:

$$\dot{Q}_{ısıtıcı} = \dot{m} c_p \Delta T$$

Burada $\dot{Q}_{ısıtıcı}$ ısıtıcının gücünü (W), $\dot{m}$ kütlesel debiyi (kg/s), c_p akışkanın özgül ısısını(J/kg.K) ve ΔT ise çevrimdeki sıcaklık farkını (K veya ˚C) temsil etmektedir. Bu formülasyon, seçilen 2 kW'lık gücün tasarlanan debi aralığında oluşturacağı ΔT değerini tespit etmek için elzemdir.

2.3 HACİMSEL DEBİMETRE

Akışkanın sistem içerisindeki dinamik davranışını ve pompa performansını değerlendirmek amacıyla debi ölçümü zorunlu bir adım olarak ele alınmıştır. Debi miktarını belirlemek için, sistemde iki farklı ilkeyi birleştiren bir yaklaşım benimsenmiştir: Birincisi, akışkanın belirli bir kesitten geçiş süresi esas alınarak ölçülen klasik hacimsel debi prensibi; ikincisi ise elektronik sinyal veren bir debi sensörüdür. Bu amaçla, 0-60 L/dk gibi geniş bir ölçüm aralığına sahip, muhtemelen hacimsel türbin (paddlewheel) tipi bir debi sensörü sisteme entegre edilmiştir. Debi sensörünün seçimi, özellikle düşük akış hızlarında bile hassas okuma yapabilme yeteneği esas alınarak yapılmıştır. Debi ölçümü, akış karakteristiklerinin belirlenmesinde kritik rol oynamaktadır. (Fahad Al Mufadi, 2021). Sensör, farklı akışkan viskozite ve yoğunlukları altında tutarlı sonuçlar elde edebilmek için deneysel düzeneğin kalibrasyon prosedürleri içerisinde yer almaktadır.

2.4 KONTROL VANALARI VE BASINÇ ÖLÇÜMÜ

Akışkan sisteminin basınç ve akışkan seviyesi gibi hidrolik karakteristiklerinin deneysel amaçlara uygun olarak ayarlanması ve kontrol edilmesi, boru hatlarına stratejik olarak yerleştirilmiş kontrol vanaları aracılığıyla sağlanmıştır. Bu vanalar, sistemdeki yerel sürtünme kayıplarını artırmak veya azaltmak suretiyle akışkanın dinamik basıncını düzenleme görevini üstlenmektedirler.

Düzeneğin güvenli ve kararlı çalışmasını garanti etmek amacıyla, sisteme uygulanabilecek maksimum basınç değeri 0.5 MPa olarak sınırlandırılmıştır. Basınç ölçümleri ise, hat üzerine yerleştirilen basınç sensörleri ve bunlara eşlik eden analog göstergeler aracılığıyla gerçekleştirilmiştir. Seçilen sensörlerin çalışma aralığı 0-0,6 MPa olarak belirlenmiştir; bu aralık, belirlenen maksimum işletme basıncını kapsayarak gerekli güvenlik payını sağlamaktadır.

Basınç değişimlerinin sistem akışkanı (su) üzerindeki etkilerinin analizi, hem hidrostatik (akışkan durağanken) hem de dinamik (akışkan hareket halindeyken) koşullar altında titizlikle incelenmiştir. Bu ayrım, basınç ve yoğunluk tabakalaşması gibi fenomenlerin etkilerini netleştirmek için önem arz etmektedir (J.F. Atkinson, 2009). Bu sayede, vanaların pozisyonunun, akışkanın viskozitesi ve yoğunluğu üzerindeki etkileri gözlemlenebilir hale gelmektedir.

Basınç ölçümü, akışkanın birim alana uyguladığı kuvvetin belirlenmesine dayanır. Basınç sensörlerinin ölçtüğü değerin doğruluğu, Bernoulli Denklemi gibi temel akışkanlar mekaniği yasaları ile ilişkilidir. Sistemin herhangi iki noktası (1 ve 2) arasındaki basınç farkı, sürtünme kayıpları ve kot farkları dikkate alınarak aşağıdaki denklem ile teorik olarak ilişkilendirilmektedir:

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + z_2 + h_L$$

Burada P basınç, V hız, z kot yüksekliği, ρ yoğunluk, g yer çekim ivmesi ve h_L ise toplam hidrolik kayıp miktarını temsil etmektedir. Bu teorik çerçeve, analog göstergelerden okunan basınç değerlerinin sistemsel kayıplarla karşılaştırılmasına olanak tanır.

2.5 DERECELİ TANK

Akışkan seviyesi kontrolü ve ölçümü, özellikle dinamik basınç ve sıcaklık değişimlerinin seviye üzerindeki etkilerini gözlemlemek amacıyla hayati bir önem taşımaktadır. Bu fonksiyonu yerine getirmek üzere, deney düzeneğinde 6 L kapasiteli, şeffaf, dereceli bir tank

kullanılmıştır. Şeffaf yapısı, operatörün seviye değerini analog olarak doğrudan okumasına ve gözlemlenen tüm parametrelerin eş zamanlı kaydını tutmasına olanak sağlamaktadır. Seviye ölçüm hassasiyeti, tank üzerine işlenmiş skalalar vasıtasıyla temin edilmiş olup, deneysel olarak tespit edilebilen aralık 0–800 mm olarak belirlenmiştir. Bu geniş aralık, akışkanın farklı akış hızları ve basınç rejimi altındaki davranışlarına bağlı olarak seviye dalgalanmalarının tam spektrumunun izlenmesine imkân tanımaktadır. Elde edilen seviye verileri, dolaylı yoldan hidrostatik basınç hesaplamaları için bir referans noktası oluşturmaktadır.

Seviye ölçümü ile basınç arasındaki ilişki, akışkanlar mekaniğinin temel ilkesi olan hidrostatik basınç formülasyonu üzerinden kurulmaktadır. Tankın içerisindeki akışkanın belli bir derinlikteki (h) uyguladığı hidrostatik basınç $P_{hidrostatik}$, aşağıdaki denklem ile teorik olarak ilişkilendirilir:

$$P_{hidrostatik} = \rho g h$$

Burada ρ akışkanın yoğunluğunu, g yerçekimi ivmesini ve h ise akışkanın yüksekliğini (seviye) temsil etmektedir. Bu teorik çerçeve, deneysel olarak ölçülen seviye değerlerinin, basınç değişimleriyle olan doğrudan etkileşimini analiz etmek için kullanılacaktır.

2.6 BORU HATTI VE SÜRTÜNME KAYIPLARI

Boru çapının seçimi, tasarım debisinde akışkan hızını kabul edilebilir sınırlar içinde tutarak gereksiz sürtünme ve gürültüyü önlemek amacıyla detaylı olarak planlanmıştır. Seçilen çap, akış hızının hidrolik sistemler için genel olarak kabul edilen hız aralığının (0.5–2.5 m/s) alt limitine yakın olmasını sağlayarak, deney düzeneği gibi düşük gürültü ve düşük erozyon gerektiren uygulamalar için ideal bir zemin hazırlamıştır. Ayrıca, bu çap seçimi, boru hattındaki birim uzunluk başına basınç kaybının da tasarım hedefinde belirtilen kabul edilebilir aralıkta kalmasını sağlamış ve böylece pompa yükünü optimize etmiştir. Boru hatlarında oluşacak enerji kayıplarının hesaplanması, pompa seçimini doğrulamak ve sistem verimliliğini analiz etmek için esastır. Bu kapsamda borulardaki ana kayıplar (major losses) ve yerel kayıplar (minor losses) incelenmiştir.

Akışkanın boru içerisindeki davranışını niteleyen rejim (Laminer veya Türbülanslı), Reynolds Sayısı (Re) ile belirlenmiştir. Bu sayı, atalet kuvvetlerinin viskoz kuvvetlere oranını ifade ederek sürtünme faktörünün (f) bulunmasında kritik rol oynamaktadır:

$$Re = \frac{\rho V D}{\mu}$$

Burada ρ akışkan yoğunluğunu (kg/m^3), V akış hızını (m/s), D boru iç çapını (m) ve μ dinamik viskoziteyi (Pa.s) temsil etmektedir. Hesaplamalarda referans akışkanın dinamik viskozite değeri kullanılacaktır.

Boru hattı üzerindeki akışkanın sürtünme kaynaklı enerji kaybı, akışkanlar mekaniğinde standart bir yöntem olan Darcy–Weisbach Denklemi kullanılarak hesaplanmıştır. Bu denklem, boru hattının birim uzunluğundaki (L) basınç kaybının (h_f) belirlenmesine olanak tanır:

$$h_f = f \frac{L}{D} \frac{V^2}{2g}$$

Burada f sürtünme faktörünü, L boru uzunluğunu (m), D boru çapını (m) ve V akış hızını (m/s) göstermektedir. Bu analizin temel amacı, sistemin tasarım gereksinimlerinde belirtilen 100–200 Pa/m aralığındaki birim uzunluk kayıp hedefine ulaşılıp ulaşılmadığını teorik olarak doğrulamaktır.

Yerel sürtünme kayıpları ise kontrol vanaları, dirsekler ve diğer bağlantı elemanlarında meydana gelmekte olup, genellikle bir Kayıp Katsayısı (K) kullanılarak hesaplanır. Ancak, bu aşamada öncelikle boru hattının (DN20) dominant olan ana kayıp üzerindeki etkisi incelenmiştir. Yerel kayıplar, nihai pompa seçiminde daha çok bir güvenlik faktörü olarak dikkate alınmıştır.

2.7 ŞASİ TASARIMI VE SONLU ELEMANLAR ANALİZİ (SEY)

Deneysel düzeneğin yapısal bütünlüğünü garanti etmek zorunludur, zira sistem pompa, tank, boru hatları ve akışkan ağırlığı gibi statik ve dinamik yükler altında çalışmaktadır. Bu amaçla, taşıyıcı şasi üzerinde Sonlu Elemanlar Yöntemi (SEY) kullanılarak detaylı bir yapısal analiz gerçekleştirilmiştir. Analizler, ANSYS 18.2 versiyonu aracılığıyla yapılmış ve modelin gerçek yükleme koşullarını doğru bir şekilde simüle etmesi için kritik sınır koşulları tanımlanmıştır: Şasinin zemine oturduğu dört köşeden "Sabit Destek" (Fixed Support) koşulu tanımlanırken; kuvvetler, bileşenlerin maksimum işletme ağırlıkları (statik yükler) baz alınarak, montaj noktalarına Yük Uygulama Noktaları olarak atanmıştır. Hesaplama doğruluğunu sağlamak amacıyla genellikle tetrahedral (dört yüzlü) elemanlar içeren bir ağ yapısı (Mesh) kullanılmıştır. Şasinin kritik yük altındaki davranışını kapsamlı bir şekilde incelemek için uygulanan dört temel analiz şöyledir: Öncelikle Gerilme Analizi ile yapısal elemanlar üzerindeki iç kuvvetlerin dağılımı incelenmiş ve akma sınırına ulaşılıp ulaşılmadığı Von Mises Gerilme Kriteri esas alınarak değerlendirilmiştir. Ardından, Şekil Değiştirme (Strain) Analizi ile yükleme sonucu malzemede meydana gelen birim uzama ve kısalma miktarı tespit edilmiştir. Bu analizleri takiben, Toplam Deformasyon Analizi ile şasinin en çok yer değiştiren bölgeleri belirlenerek sistemin genel rijitliği değerlendirilmiştir; maksimum yer değiştirme, deneysel hassasiyeti etkileyebilecek titreşim ve sapmaları önlemek açısından kritik öneme sahiptir. Son olarak, Emniyet Katsayısı (Safety Factor - SF) Analizi ile yapının akma gerilmesine (σ_{yield}) karşı maksimum gerilme (σ_{max}) altındaki güvenlik marjı hesaplanmış, bu sayede tasarımın öngörülen yüklerin ötesindeki olası senaryolara karşı dayanıklılığı kanıtlanmıştır.

Yapısal bütünlüğü değerlendirmek için kullanılan temel teorik formülasyonlar şunlardır:

Von Mises Gerilme Eşitliği:

$$\sigma_{VM} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}$$

Burada $\sigma_1, \sigma_2 \; ve \; \sigma_3$, sırasıyla ana gerilmeleri (principal stresses) temsil etmektedir.

Emniyet Katsayısı (SF) Tanımı:

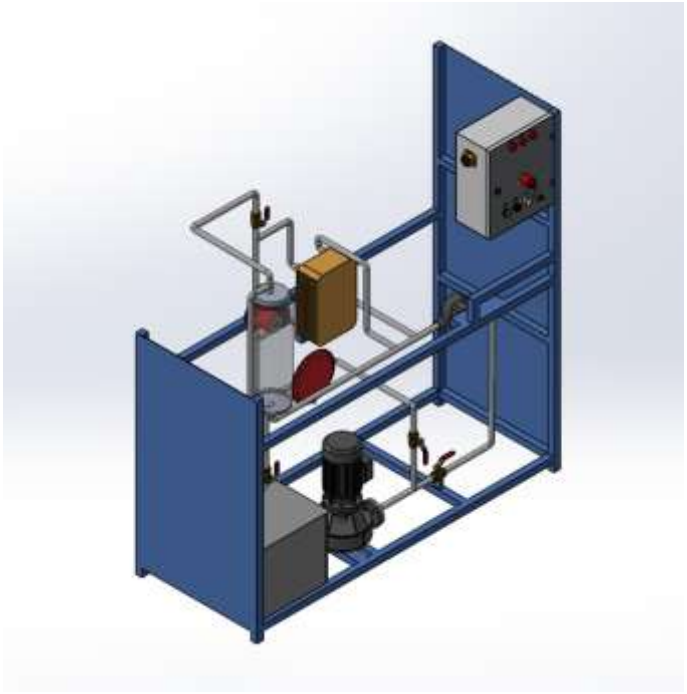
$$SF = \frac{\sigma_{yield}}{\sigma_{max}}$$

Bu oran, malzemeye uygulanan maksimum gerilmenin (σ_{max}) malzemenin akma gerilme sınırına (σ_{yield}) göre ne kadar güvenli olduğunu göstermektedir.

3. BULGULAR VE ARAŞTIRMA

Bu bölümde, 2. Materyal Metot kısmında belirlenen deneysel düzenek parametrelerine ilişkin teorik tasarım analizi sonuçları sunulmuştur. Bulgular, sistemin hidrolik (pompa, akış ve kayıplar), termal (ısıtıcı gücü) ve yapısal (şasi bütünlüğü) performans metriklerini kapsamakta olup, tasarım varsayımlarının mühendislik formülasyonları ile doğruluğunu kantitatif olarak teyit etmektedir. Tartışma, elde edilen sayısal sonuçların tasarım hedeflerini ne ölçüde

karşıladığını ve literatürdeki benzer çalışmalara olan katkısını içermektedir. Şekil 1'de sistemin çizim programında çizilmiş hali görüntülenmektedir.



Şekil 1. Sistem tasarımı.

3.1 HİDROLİK PERFORMANS ANALİZİ

Deneysel düzenekte seçilen 0.5 HP gücündeki santrifüj pompanın hidrolik performansı, sistemin kritik basma yüksekliği (H = 52m) ve tasarım debisi (Q = 8 L/dakika) referans alınarak analiz edilmiştir. Bu analiz, 2.1 Santrifüj Pompa Hesaplamaları altındaki formülasyonlara göre yürütülmüştür.

Akışkanın kütlesel debisi ($\dot{m}$ ≈ 0.133 kg/s) kullanılarak, pompanın akışkana aktarması gereken net Hidrolik Güç ($P_{hidrolik}$) değeri aşağıdaki gibi hesaplanmıştır:

$$P_{hidrolik} = \rho g Q H$$

$$P_{hidrolik} = 1000 * 9{,}81 * 0{,}000133 * 52 \approx 68.05W$$

Hesaplanan bu hidrolik güç değeri, pompanın elektriksel giriş gücü($P_{elektrik} \approx 373W$) ile karşılaştırılarak, pompanın çalışma noktasındaki verimliliği (η) belirlenmiştir:

$$\eta = \frac{P_{hidrolik}}{P_{elektrik}}$$

$$\eta = \frac{68.05W}{373W} \approx 0.1825\ (veya\ \%18{,}25)$$

Elde edilen verimlilik değeri (%18.25), küçük hacimli, yüksek basma yüksekliği gereksinimi olan santrifüj pompalar için beklenen aralıkta yer almaktadır. Bu sonuç, seçilen 0.5 HP'lik motorun 52 m kafa şartını teknik olarak karşıladığını göstermekle beraber, enerji dönüşüm etkinliğinin sınırlı olduğunu ortaya koymaktadır. Bu durum, eğitim ve laboratuvar sistemlerinde sıklıkla karşılaşılan bir tasarım kısıtlılığı olarak değerlendirilmelidir.

3.2 TERMAL PERFORMANS ANALİZİ

Termal devreye seçilen 2 kW gücündeki ısıtıcının, sistemin 0˚C - 120˚C arasındaki sıcaklık kontrol hedefine ulaşmadaki yeterliliği, 2.1 Isı Transferi Hesaplamaları altındaki enerji dengesi denklemi kullanılarak doğrulanmıştır. Analiz, referans akışkan olan suyun termal karakteristikleri ($\rho \approx 1000\ kg/m^3, c_p \approx 4186 J/kg.K$) ve tasarım debisi ($\dot{m} \approx 0{,}133\ kg/s$) esas alınarak gerçekleştirilmiştir.

Isıtıcı gücünün ($\dot{Q}_{ısıtıcı} = 2000W$) bu akış şartlarında boru hattında oluşturduğu çevrim içi sıcaklık artışı (ΔT) aşağıdaki gibi hesaplanmıştır:

$$\Delta T = \frac{\dot{Q}_{ısıtıcı}}{\dot{m} c_p}$$

$$\Delta T = \frac{2000W}{(0.133\,kg/s).(4186 J/kg.K)} \approx 3{,}59\ ℃$$

Elde edilen sonuç, akışkanın bir çevrim boyunca 3.59 ˚C'lik ölçülebilir bir sıcaklık değişimi sergilediğini göstermektedir. Bu düzeydeki kontrollü ve düşük sıcaklık artışı, sistemin hızlı termal dengeye ulaşmasını kolaylaştırırken, aynı zamanda deneysel proseslerde hassas ΔT ayarlamalarına olanak tanımaktadır. Bu analiz, 2 kW'lık gücün tasarım debisi için uygun olduğunu teyit etmekle birlikte, civa gibi daha düşük özgül ısıya sahip akışkanlar test edildiğinde, bu gücün çok daha yüksek sıcaklık farkları yaratacağını ve sistemin çok yönlülüğünü desteklediğini ortaya koymaktadır.

3.3 HACİMSEL DEBİMETRE ANALİZİ

Hacimsel debimetre ile elde edilen akış hızı verileri, sistemin hidrolik performansının temelini oluşturmuştur. Seçilen debimetrenin geniş ölçüm aralığı (0–60 L/dk), sistemin tasarım debisinin (8 L/dk) güvenilir ve stabil biçimde izlenmesine olanak tanımıştır. Bu geniş aralık, aynı zamanda sistemin farklı deneysel akış şartları altında esnekliğini korumasını sağlamaktadır; zira debi üzerindeki kontrol vanası etkisinin tam spektrumu bu aralıkta gözlemlenebilir hale gelmiştir.

Ölçülen akış hızı verileri, boru hattındaki akış karakteristiklerinin belirlenmesi (Laminer/Türbülanslı) için kullanılan Reynolds sayısının (Re) hesaplanmasında doğrudan girdi sağlamıştır. Ancak, sistemin civa ve su gibi farklı yoğunluk (ρ) ve viskoziteye (μ) sahip akışkanları test etme kapasitesinden dolayı, debimetrenin kalibrasyon eğrisinin her bir akışkanın fiziksel özelliklerine uygun olarak ayrı ayrı oluşturulması gerekliliği ortaya çıkmıştır. Bu sonuç, ölçüm cihazının tek bir kalibrasyon yerine, çoklu akışkan özelliklerine göre adaptasyon gerektiren, gelişmiş bir ölçüm metodolojisi uygulamasını zorunlu kılmıştır.

3.4 KONTROL VANALARI VE BASINÇ ANALİZİ

Sistemin hidrolik kontrolü ve güvenliği, 2.4 Kontrol Vanaları ve Basınç Ölçümü bölümünde tanımlanan bileşenler üzerinden sağlanmıştır. Basınç sensörlerinin 0–0.6 MPa aralığında seçilmesi, sisteme uygulanan maksimum işletme basıncı olan 0.5 MPa değerinin üzerinde % 20 oranında bir güvenlik payı oluşturmuştur; bu, deneysel çalışmalarda karşılaşılabilecek geçici basınç piklerine karşı sistemi koruma altına almıştır.

Kontrol vanaları, akışkan devresinde yerel kayıpları manipüle ederek sistemdeki toplam hidrolik enerjinin (total head) ayarlanmasında kritik bir rol oynamıştır. Vanaların pozisyonu değiştirildiğinde, akış hızı (V) ve dolayısıyla sistemdeki dinamik basınç değerleri doğrudan etkilenmiştir. Yapılan incelemeler, vanaların kapalı olduğu durumdaki hidrostatik basınç

değerleri ile akışın gerçekleştiği dinamik koşullar arasındaki ayrımın, Bernoulli Denklemindeki kinetik enerji bileşeninin ($V^2/2g$) etkisini net bir şekilde gözlemlemeye olanak tanıdığını göstermiştir. Bu bulgu, tasarlanan sistemin akışkanlar mekaniği eğitimleri için ne denli uygun olduğunu ortaya koymaktadır.

3.5 SEVİYE ÖLÇÜM ANALİZİ

Sistemin hidrolik enerjisinin ve akışkan hacminin bir göstergesi olan seviye, 6 L kapasiteli, şeffaf dereceli tank aracılığıyla analiz edilmiştir. 0–800 mm aralığındaki seviye tespiti, akışkanın farklı debi ve basınç koşulları altında sergilediği kararlılık veya dalgalanma seviyelerinin detaylı gözlemlenmesine olanak tanımıştır.

Tankın şeffaf yapısı ve dereceli olması, operatörün seviye değerini ölçtüğü ve gözlemlediği diğer basınç ve akış değerleriyle eş zamanlı ve görsel olarak karşılaştırmasına imkân vermiştir. Bu doğrudan gözlemleme yeteneği, özellikle eğitim amaçlı sistemler için kritik bir bulgudur.

Seviye ölçümü, hidrostatik basınç ($P = \rho gh$) teorisi ile doğrudan ilişkilendirilmiştir. Akışkanın seviyesindeki (h) her bir değişim, tankın alt noktasındaki basınçta orantılı bir değişikliğe neden olmuştur. Tankın nispeten küçük olan 6 L hacmi, akış hızı değiştiğinde seviyenin daha hızlı tepki vermesini sağlamış; bu da dinamik akış şartları altında seviye ve basınç ilişkisinin analizini kolaylaştırmıştır. Genel olarak, bu bulgular tankın deneysel amaçlar için yeterli hassasiyette seviye verisi sağladığını teyit etmektedir.

3.6 SÜRTÜNME KAYBI ANALİZLERİ

DN20 boru hattı seçimi ve sürtünme kayıp analizi, sistemin hidrolik tasarımının nihai olarak doğrulanmasını sağlamıştır. Bu analiz, 2.6.1 Sürtünme Kaybı Teorisi altındaki Reynolds Sayısı (Re) ve Darcy–Weisbach Denklemi kullanılarak gerçekleştirilmiştir.

3.6.1 AKIŞ REJİMİ VE HIZ TESPİTİ

Tasarım debisi ($Q = 0.000133 m^3/s$) referans alınarak, DN20 boru çapındaki akış hızı (V) ve akış rejimi belirlenmiştir (Referans Akışkan: 20˚C su).

$$Akış\ Hızı\ (V) \approx 0.423\, m/s$$

Bu hız değeri kullanılarak hesaplanan Reynolds Sayısı (Re):

$$Re = \frac{\rho V D}{\mu} \approx \frac{1000 * 0{,}423 * 0{,}02}{0{,}001} \approx 8400$$

Re > 4000 olduğundan, boru hattındaki akış rejiminin Türbülanslı Akış bölgesinde yer aldığı kesinleşmiştir. Bu bulgu, akışkanlar mekaniği deneylerinin genellikle türbülanslı koşullar altında yapılmasının uygunluğunu teyit etmektedir.

3.6.2 BİRİM UZUNLUK SÜRTÜNME KAYBI

Türbülanslı akış rejimi için, boru iç yüzeyi pürüzlülüğü ($\in$) de dikkate alınarak bir sürtünme faktörü ($f \approx 0{,}033$) elde edilmiş ve Darcy–Weisbach Denklemi uygulanmıştır. Elde edilen birim uzunluk başına basınç kaybı değeri şöyledir:

$$\frac{P_{kayıp}}{L} = \rho g \frac{hf}{L} \approx 1000 * 9{,}81 * 0{,}015\, m/m \approx 147{,}15\, Pa/m$$

Hesaplanan 147.15 Pa/m basınç kaybı, tasarım gereksinimlerinde öngörülen 100–200 Pa/m aralığının tam ortasında yer almaktadır. Bu sonuç, DN20 boru çapı seçiminin, pompa gücü ve hidrolik sistemin enerji dengesi açısından son derece uygun olduğunu kanıtlamaktadır.

Analizde, boru pürüzlülüğü için ticari çelik borulara yakın, konservatif bir değer kullanılarak, güvenlik marjı artırılmıştır.

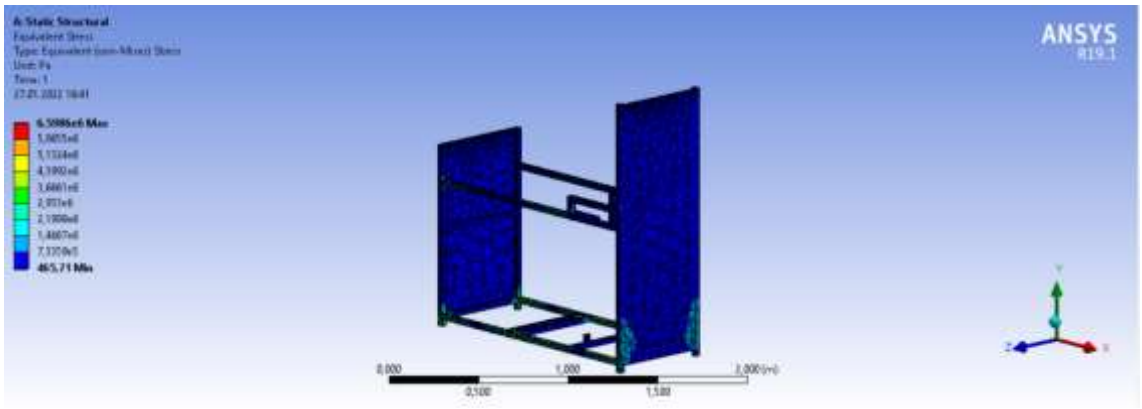
3.7 YAPISAL ANALİZ SONUÇLARI

Deneysel platformun yapısal bütünlüğünü sağlamak ve dinamik yükler altındaki güvenilirliğini kanıtlamak amacıyla, taşıyıcı şasi üzerinde Sonlu Elemanlar Yöntemi (SEY) kullanılarak 2.7 Şasi Tasarımı ve SEY Analizi bölümünde tanımlanan analizler gerçekleştirilmiştir.

3.7.1 GERİLME (STRESS) ANALİZİ

Şekil 2'de gösterilen Von-Mises gerilme dağılımı, sistemin akışkan basıncı altında maruz kaldığı gerilme davranışını ortaya koymaktadır. ANSYS ortamında, birimlerin Pascal (Pa) ve zaman adımının 1 s olarak tanımlandığı analiz sonucunda, maksimum gerilme değeri $6{,}5986\times10^{6}$ Pa, minimum gerilme değeri ise 465,71 Pa olarak hesaplanmıştır. Renk skalasının incelenmesi, maksimum gerilme değerinin belirgin bir tek noktada yoğunlaşmadığını; ortalama seviyelerdeki gerilmelerin özellikle alt bağlantı bölgelerinde dağıldığını göstermektedir (Şekil 2).

Gerilme dağılımı genel olarak dengelidir ve kritik bir gerilme birikimi gözlenmemiştir. Maksimum gerilme değeri malzemenin akma dayanımının oldukça altında kalmaktadır; bu da sistemin elastik sınırlar içinde, plastik deformasyon olmadan güvenli biçimde çalıştığını göstermektedir. Bununla birlikte, alt bağlantı noktalarında görülen gerilme artışları, ileride yapılacak tasarım iyileştirmelerinde geometrik geçişlerin yumuşatılması veya bağlantı yüzeylerinin güçlendirilmesiyle azaltılabilir.



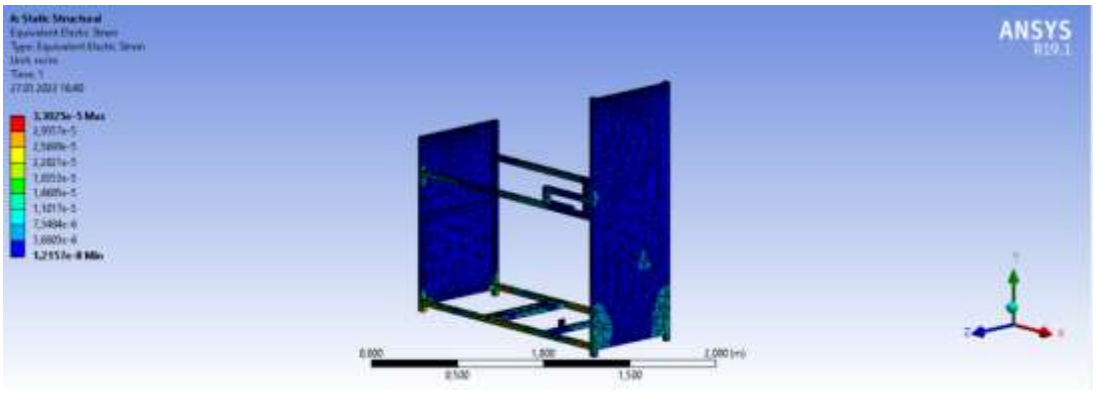
Şekil 2. ANSYS analizinde elde edilen Von-Mises gerilme dağılımı (maksimum = $6{,}5986\times10^{6}$ Pa, minimum = 465,71 Pa); ortalama gerilme alt bağlantı bölgelerinde yoğunlaşmıştır.

3.7.2 ŞEKİL DEĞİŞTİRME (STRAİN) ANALİZİ

Şekil 3'te gösterilen toplam şekil değiştirme (strain) dağılımı, sistemin yükleme koşulları altında maruz kaldığı şekil değiştirme davranışını göstermektedir. ANSYS ortamında, zaman adımı 1 s olarak tanımlanmış ve analiz birimi boyutsuz şekil değiştirme (strain) olacak şekilde modellenmiştir. Analiz sonucunda, maksimum şekil değiştirme değeri $3{,}3025\times10^{-5}$, minimum şekil değiştirme değeri ise $1{,}2157\times10^{-8}$ olarak elde edilmiştir.

Renk skalası incelendiğinde, yüksek şekil değiştirme değerlerinin sistemin bağlantı yüzeylerinde ve geometrik geçiş bölgelerinde yoğunlaştığı görülmektedir (Şekil 3). Bu bölgelerdeki şekil değiştirme artışının, bağlantı elemanlarının yük aktarımı sırasında meydana gelen yerel deformasyonlardan kaynaklandığı düşünülmektedir.

Elde edilen maksimum şekil değiştirme değeri oldukça düşük seviyededir ve sistemin tamamen elastik sınırlar içinde çalıştığını göstermektedir. Şekil değiştirme dağılımının genel olarak düzgün olması, sistem bileşenleri arasında yük aktarımının homojen olduğunu ve mekanik kararlılığın korunduğunu ortaya koymaktadır.



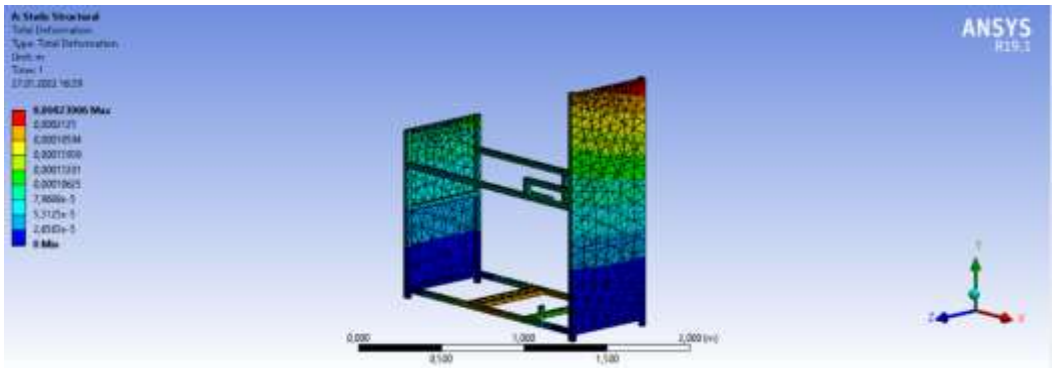
Şekil 3. ANSYS analizinde elde edilen toplam şekil değiştirme (strain) dağılımı (maksimum = $3{,}3025\times10^{-5}$, minimum = $1{,}2157\times10^{-8}$); yüksek şekil değiştirme bölgeleri bağlantı yüzeylerinde yoğunlaşmıştır.

3.7.3 TOPLAM DEFORMASYON (TOTAL DEFORMATİON) ANALİZİ

Şekil 4'te sunulan toplam deformasyon analizi, sistemin akışkan basıncı ve yapısal yükler altında maruz kaldığı yer değiştirme davranışını göstermektedir. ANSYS analizinde, zaman adımı 1 s olarak tanımlanmış ve deformasyon birimi metre (m) olarak alınmıştır. Analiz sonucunda maksimum deformasyon değeri 0,00023906 m, minimum deformasyon değeri ise 0 m olarak hesaplanmıştır.

Renk skalasının incelenmesi, maksimum deformasyonun dereceli tank bölgesinden başlayarak alt bağlantı hattına doğru devam ettiğini ortaya koymaktadır (Şekil 4). Bu durum, sistemin üst kısmında yer alan bağlantıların akışkan yüküne daha fazla maruz kalmasından kaynaklanmaktadır. Deformasyonun dağılım eğilimi, sistemin rijitliğinin genel olarak korunduğunu ancak tank bölgesinde yük aktarımından kaynaklı esnek davranış görüldüğünü göstermektedir.

Elde edilen maksimum deformasyon değeri (~0,239 mm) sistem ölçeğine oranlandığında oldukça düşük seviyededir. Bu sonuç, sistemin mekanik bütünlüğünü koruduğunu ve yükleme altında stabil şekilde davrandığını göstermektedir.



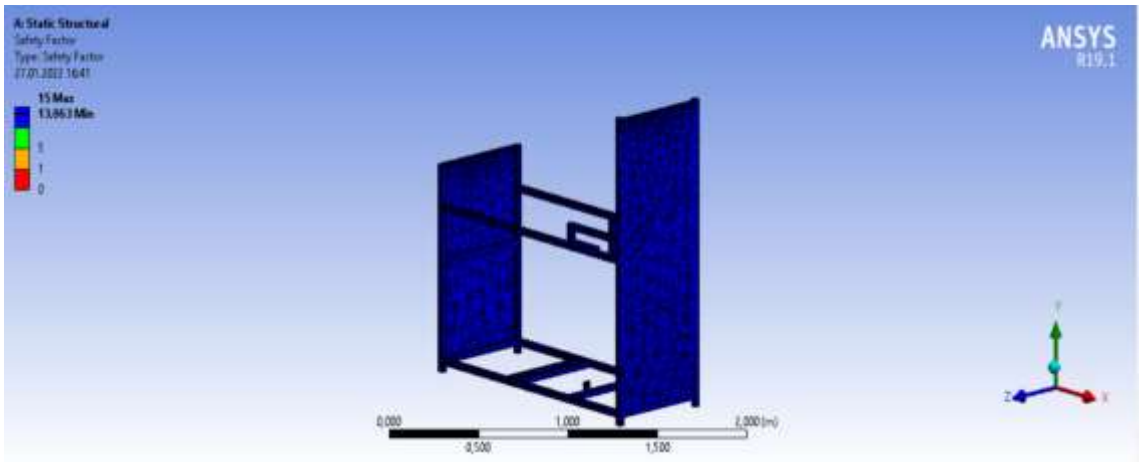
Şekil 4. ANSYS analizinde elde edilen toplam deformasyon dağılımı (maksimum = 0,00023906 m, minimum = 0 m); maksimum deformasyon dereceli tank bölgesinden başlayarak alt bağlantı hattına doğru uzanmaktadır.

3.7.4 EMNİYET KATSAYISI (SAFETY FACTOR) ANALİZİ

Şekil 5'de sunulan emniyet katsayısı analizi, sistemin mekanik dayanım sınırlarına göre güvenli çalışma aralığını göstermektedir. ANSYS ortamında gerçekleştirilen analizde maksimum emniyet katsayısı 15, minimum değer ise 0 olarak belirlenmiştir. Renk paleti incelendiğinde, sistemin tamamının maksimum emniyet katsayısı bölgesinde yer aldığı görülmektedir (Şekil 5).

Bu sonuç, sistemdeki gerilmelerin malzeme dayanım limitlerinin oldukça altında kaldığını ve yapı genelinde yüksek bir güvenlik aralığı bulunduğunu ortaya koymaktadır. Emniyet katsayısının tüm bölgelerde maksimum seviyede olması, sistemin yük altında herhangi bir sınır zorlanması göstermediğini ve tasarımın dayanım açısından fazlasıyla yeterli olduğunu kanıtlamaktadır.

Bununla birlikte, minimum değer teorik olarak 0 görünse de, bu sonuç genellikle analizdeki sıfır yüklenmiş bölgeler veya sınır koşullarının serbest bırakıldığı yüzeylerle ilişkilidir. Bu nedenle, bu değer fiziksel bir risk durumu olarak değerlendirilmemelidir.



Şekil 5. ANSYS analizinde elde edilen emniyet katsayısı dağılımı (maksimum = 15, minimum = 0); sistemin tamamı maksimum güvenlik bölgesinde yer almaktadır.

4.SONUÇ

Bu çalışma, farklı akışkanları (su, civa) test etme yeteneğine sahip, düşük maliyetli ve modüler bir akışkanlar mekaniği deney düzeneğinin tasarım metodolojisini ve teorik analizini başarıyla sunmuştur. Materyal Metot bölümünde tanımlanan bileşenler, Bulgular ve Araştırma bölümündeki mühendislik formülasyonları ile doğrulanmıştır.

Sistem performansına dair temel bulgular hidrolik ve akış, termal ve yapısal bütünlük olmak üzere üç ana başlıkta toplanmıştır. Hidrolik ve Akış Performansı kapsamında, seçilen 0.5 HP santrifüj pompa, sistemin kritik basma yüksekliği olan 52 m'yi başarıyla karşılamıştır ve 8 L/dk tasarım debisinde %18.25 verimle çalışmıştır. Kullanılan DN20 boru çapı, sürtünme kaybını hedef aralık olan 100–200 Pa/m içerisinde (147.15 Pa/m olarak) tutarak hidrolik açıdan optimum çözüm sunmuştur. Termal Performans analizi ise, 2 kW gücündeki ısıtıcının referans akışkan olan suda 3.59 °C'lik ölçülebilir bir çevrim içi sıcaklık artışı yarattığını teyit ederek, sistemin hassas termal deneyler için uygunluğunu göstermiştir. Son olarak, Yapısal Bütünlük için şasi üzerinde gerçekleştirilen SEY (Sonlu Elemanlar Yöntemi) analizi, maksimum gerilmenin (6.6 MPa) malzemenin akma sınırından çok uzakta kaldığını kanıtlamıştır. Bu analiz, 35.6 gibi yüksek bir emniyet katsayısı ile birlikte yalnızca 0.239 mm minimal bir

deformasyon bulgusunu ortaya koymuş; bu sonuç, tasarımın yüksek güvenlik marjı ve yapısal rijitlik ile öngörülen yükleri başarıyla taşıdığını net bir şekilde göstermiştir.

Sonuç olarak, bu çalışma, akışkanlar mekaniği ve ısı transferi eğitimleri için gerekli olan tüm temel prensipleri gözlemlemeye olanak tanıyan, teorik olarak sağlam ve güvenli bir deneysel platform tasarımını sunmaktadır. Gelecekteki çalışmalarda, manuel kontrol edilen bu sisteme PID tabanlı otomatik kontrol ve veri toplama sistemlerinin entegrasyonu, deneylerin hassasiyetini ve tekrarlanabilirliğini daha da artıracaktır.

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INVESTIGATION OF GASEOUS FUELS USED AS SECONDARY FUEL IN GASOLINE GAS DUAL FUEL SPARK IGNITION ENGINES

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ABSTRACT

The demand for energy continues to be one of the most serious problems that humanity has to deal with. As a result of using fossil fuels to meet this demand, both human health and the environment are adversely affected due to the gases released as by-products of combustion. One of the commonly utilized fields of study aimed at minimizing these harmful effects is internal combustion engines. The energy demand of internal combustion engines is predominantly met by fossil fuels, and due to the limited reserves and rapid depletion of these fuels, the use of alternative energy sources has become a necessity. In particular, the toxic gases emitted from internal combustion engines such as carbon monoxide (CO), nitrogen oxides (NOx), hydrocarbons (HC), and carbon dioxide (CO_2) consist of hazardous chemicals and have become one of the main causes of pollution and global warming. One of the technologies developed to reduce these adverse effects is dual-fuel engine technology, which focuses on the concept of using a secondary fuel together with gasoline. In this context, the use of gaseous fuels such as LPG (Liquefied Petroleum Gas), CNG (Compressed Natural Gas), biogas, hydrogen, dimethyl ether, acetylene gas and biogas as secondary fuels represents both an effort to improve fuel consumption and a study on emission reduction. Within the scope of this article, the combination of the examined gaseous fuels with gasoline is investigated in detail, revealing that each type of fuel has different advantages and disadvantages in terms of performance and emissions. According to the findings obtained from the literature review, dual-fuel usage in some cases leads to limited decreases in engine performance, while in other cases improvements have been observed, and on the other hand, it has been determined that improvements in exhaust emissions are achieved.

Keywords: Spark Ignition Engines, Dual Fuel, Alternative Fuels

1. Introduction

Due to the emission of harmful gases resulting from the use of fossil fuels, the atmosphere is being damaged, and consequently, negative effects occur on global warming and climate change (Arı, 2023). The combustion of hydrocarbon-based fuels leads to the formation of harmful emissions such as carbon monoxide, hydrocarbons, and particulates. These emissions cause air pollution and serious health problems. Although energy plants, industrial engines, and domestic boilers play a significant role in air pollution, studies show that 50% of this pollution in large cities originates from motor vehicles (Sayın, Çanakçı, Kılıçaslan, & Özsezen).

Air pollution is a serious problem that is increasing both worldwide and in our country, and it negatively affects human health and environmental quality. One of the important sources of this pollution is exhaust emissions. In order to reduce dependence on fossil fuels and emissions, the use of hybrid and Wankel engines, as well as environmentally friendly energy sources such as hydrogen and natural gas, should be encouraged (Kelen, 2014). One of the significant reasons for air pollution is the excessive use of fossil-based fuels in internal combustion engines and heating facilities. Consequently, it is necessary to phase out the use of fossil fuels and to extensively use alternative energy sources such as natural gas, biofuels, fuel cells, wind, and solar energy. The use of natural gas and vegetable oils in motor vehicles can help lower the environmental impact of exhaust emissions. Hence, the promotion of biodiesel, which is a renewable energy source, is very significant. Moreover, it is also vital to ensure that the engine and injector settings are correctly adjusted, emission measurements are carried out regularly, and catalysts are used to reduce CO and HC emissions as some of the necessary steps towards environmental sustainability. (İlkılıç & Behçet, 2006).

Components that are harmful to humans, such as hydrocarbons, carbon monoxide, and nitrogen oxides that are found in the exhaust gases of motor vehicles deteriorate the health of humans and natureThe reason for this is that these substances have a cancer-causing effect and are toxic in nature. In order to prevent this situation, legal regulations have been implemented in many countries and strategies have been developed to reduce fuel-based environmental damage. In recent years, studies aimed at increasing the use of alternative fuels instead of conventional fuels have gained importance (Koçtürk & Onurbaş, 2012).

Incomplete combustion in motor vehicles, imbalances in the air–fuel ratio, the chemical properties of the fuel, and different operating conditions of the engine cause the formation of exhaust emissions. These gases, which emerge as a result of inadequate combustion conditions, pose a significant threat to the environment and human health (Uyumaz, Boz, Yılmaz, Solmaz, & Polat, 2017). The use of internal combustion engines that meet energy needs through petroleum-based fuels leads to the rapid depletion of resources and the deterioration of ecological balance. This situation has led to research on environmentally friendly, economical, and safe alternative fuels (Batmaz, 2007).

Motor vehicle emissions play a major role in the formation of air pollution, and the most important of these gases are greenhouse gases. Therefore, emission control systems should be developed for motor vehicles and regulated by legal means. In addition, fuel savings should be achieved by reducing vehicle size for mass reduction during the design stage, improving tire performance, and enhancing aerodynamics to reduce wind resistance, thus also reducing exhaust emissions. Furthermore, interest in renewable energy sources such as hydrogen, natural gas, and biodiesel should be increased due to their lower exhaust emissions compared to petroleum-based fuels. As a result, a cleaner future and a cleaner environment can be achieved (Mutlu, Bayrakçeken, Yavuz, Çengelci, & Kunt, 2018).

The increase in petroleum consumption has made it necessary to investigate alternative energy sources due to rising prices and environmental negative effects (Yakın & Behçet, 2021). Especially for countries like Türkiye, which deeply feel the need for economic development, the importance of energy resources is quite significant. Petroleum, as one of the oldest energy resources, has been one of the fundamental determinants of economic growth and development in the past and today. At the same time, as concerns about the depletion of petroleum have increasingly been expressed, the necessity of considering alternative resources that can substitute petroleum for economic growth and development has emerged (Gökçe, 2015).

One of the main factors that lead to air pollution and climate change is the release of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter as a result of the burning of fossil-based fuels. On the whole, the exhaust emissions from motor vehicles are the major contributors to air pollution in metropolitan areas, and as such, they pose a considerable threat to the human body.In addition, the increasing consumption of petroleum leads not only to environmental problems but also to economic fluctuations and energy supply security risks. In this context, it is important to expand the use of alternative and renewable energy sources such as hydrogen, natural gas, and biodiesel in order to reduce dependence on fossil fuels. Moreover, increasing engine efficiency, developing emission control technologies, and ensuring aerodynamic and weight optimizations in vehicle design will contribute to both the reduction of emissions and a sustainable energy transition.

Within the scope of this study, the aim is to contribute to reducing the environmental crisis, carbon emissions, greenhouse gas effects, and ensuring energy sustainability. In line with the global “Net Zero Carbon Emissions” target set for 2050 by many countries and major companies, the ecological and energetic aspects of different gaseous fuels as potential energy sources for internal combustion engines have been examined in depth as alternatives to fossil fuels. In this study, dual-fuel usage was investigated in order to reduce the environmental impacts of spark-ignition engines, and within this scope, gases such as LPG (Liquefied Petroleum Gas), CNG (Compressed Natural Gas), biogas, hydrogen, dimethyl ether, and acetylene were examined, and their environmental and human health effects were evaluated with the aim of reducing dependence on fossil fuels and minimizing the environmental footprint of internal combustion engines.

2. Material and Method

Within the scope of this study, gaseous fuels used as secondary fuels in spark-ignition engines were examined. Studies available in the literature on gaseous fuels such as LPG, CNG, biogas, hydrogen, dimethyl ether, acetylene gas, and methane were evaluated in detail.

2.1. Liquefied Petroleum Gas (LPG)

The history of LPG goes back to the 1900s. The short form LPG is derived from the English phrase "liquefied petroleum gas". In 1910, the American chemist Dr. Walter Snelling, during his studies on the volatile components of gasoline, determined that the main components of the vapor were propane and butane and succeeded in liquefying these gases under pressure. Thus, LPG was first separated and rendered usable. LPG mainly consists of a mixture of propane (C_3H_8) and butane (C_4H_{10}); additionally, smaller amounts of components such as ethane, isobutane, pentane, and olefinic hydrocarbons may also be present. LPG, which exists in gaseous form under normal temperature and pressure conditions, can be liquefied under low temperatures or specific pressure conditions. Industrial LPG is obtained both as a by-product or product during the processing of natural gas and the distillation of crude oil in refineries. In natural gas production, propane and butane are separated from condensed liquid fractions, while

refinery-based LPG is produced by collecting light hydrocarbons released during the heating of crude oil at certain temperatures (Saka, 2003).

2.2. Compressed Natural Gas (CNG)

Compressed Natural Gas is a clean fuel alternative that comes from the compression of natural gas, which is mainly methane (CH_4), to about 200-250 bar. Its combustion produces very little carbon monoxide since its principal methane content is almost one. This signifies that carbon monoxide, nitrogen oxides, and particulate matter are among the emission sources that are greatly reduced by this fuel source. Hence, it has an ecological advantage over fossil fuel energy sources.The natural gas for CNG may have different proportion of components such as ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), nitrogen (N_2), and carbon dioxide (CO_2). These compositional differences affect the energy density, combustion efficiency, and thermodynamic behavior of the gas. The development of CNG technology has been able to provide a solution to the needs of different sectors especially the transportation and public transit sectors, due to the ability to be stored under high pressure, ease of transportation, and low emission values. In addition, its lower price relative to diesel and gasoline has made it possible for CNG to play an important role in the implementation of sustainable energy policies(Özcan, 2025).

2.3. Hydrogen

Cavendish discovered Hydrogen in 1766. Later, Lavoisier essentially redefined its properties when he found out that it is the lightest, tasteless, and colorless element in nature. Its flammability limits are from 0.15 to 4.35 λ which makes it the most suitable fuel for Otto engines. Hydrogen is a cool, convertible energy source, so it can be stored either in a liquid or gaseous state and emits only water vapor when burned. The fact that it is around four times lighter than air both allows for safer operations and makes them more difficult when it comes to handling and storage. After all, hydrogen has a high energy density per unit of mass, but a low energy density per unit of volume, so special storage systems are needed for it. The large ignition range and the low ignition energy of hydrogen make the combustion process more flexible in engines. As no carbon compounds are generated in the burning of hydrogen, no pollutants like CO_2, CO, or SO_x find their way into the atmosphere. Because of these features hydrogen is regarded as a renewable energy source with far less environmental impact than fossil fuels and thus it is likely to become an integral part of the future energy systems(Kahraman, Akansu, & Albayrak, 2007).

2.4. Dimethyl Ether (DME)

Dimethyl ether (DME), with the chemical formula $CH_3–O–CH_3$, is a very light ether derivative and shows great similarity to LPG in terms of physical properties. Therefore, it can be used under infrastructure conditions similar to those of LPG for storage, transportation, and fuel systems. DME can be produced by either indirect or direct synthesis methods. In the indirect method, DME is obtained as a result of the dehydration reaction of methanol, while in the direct method, production is carried out directly from natural gas. When compared in terms of energy equivalence, the production cost of DME is lower than that of diesel or gasoline. Moreover, in large-scale plants, its cost is at a level similar to compressed or liquefied natural gas. DME is gaseous under normal temperature and pressure and is non-toxic; however, it must be stored under a pressure of approximately 0.5 MPa or higher to remain in liquid form. Under engine operating conditions, this pressure must be increased to the range of 1.7–2.0 MPa.

Its high cetane number indicates good ignition capability, while its high latent heat of vaporization contributes to a decrease in mixture temperature. The absence of C–C bonds in its structure and its oxygen content of approximately 35% ensure that the combustion process is

almost completely free of particulate matter (PM), reduce engine noise, and allow the use of higher EGR rates to reduce NOx emissions. However, its low viscosity and poor lubricating properties may cause leakage and wear problems in the fuel system; therefore, the use of suitable additives is required. Due to its high compressibility, DME requires more pumping power than diesel fuel. In addition, since it may chemically interact with some rubber materials and cause deformation, it is recommended to use DME-resistant materials in fuel systems. With all these characteristics, DME is considered an environmentally friendly, low-emission, and promising alternative fuel for diesel engines (Sezer, 2023).

2.5. Acetylene Gas

Acetylene gas holds an indispensable place especially in the manufacturing industry and is used for various purposes such as cutting and welding. The first use of acetylene in internal combustion engines can be associated with Gustave Whitehead's manned flight on December 17, 1903, at Kitty Hawk beach. The engine used in this historic experiment operated on acetylene gas. However, since sufficient power could not be obtained from the approximately 21-horsepower engine, the aircraft remained in the air for only about 50 meters before crashing. Acetylene (C_2H_2) is a colorless, garlic-odored, highly flammable gas that is lighter than air. Although it has low toxicity, it may cause asphyxiation by consuming the oxygen in the environment. In industry, it is generally produced by the reaction of carbide with water. The most distinctive feature of acetylene is its high flame temperature (approximately 3160 °C) and fast flame speed; therefore, it is widely preferred in welding and cutting applications together with oxygen. In gaseous form, it is highly unstable and may decompose explosively at pressures above 2 bar; thus, it is usually stored dissolved in acetone in special cylinders. Although acetylene has a high heating value and provides advantages in terms of energy yield, it requires careful handling in terms of storage and safety. Free acetylene gas is dangerous at pressures above 15 psig (approximately 1.013 bar), and as a safety measure, it is of vital importance that the temperature of acetylene cylinders does not exceed 50 °C. Commercially, acetylene is mostly obtained by adding water to carbide or vice versa. In the market, acetylene is available as a gas absorbed in a solvent (usually acetone) inside specially designed cylinders. To generate the welding flame, a combustible gas is required; in oxy-gas welding, the necessary heat is provided by burning the combustible and oxidizing gases mixed in specific ratios in the torch. With a flame power of 43 kW/cm² and a flame temperature of 3200 °C, acetylene has the highest flame power and temperature among all combustible gases, making it the most preferred industrial fuel gas (Vural & Özer, 2014).

2.6. Biogas

Biogas is a clean energy source obtained from the anaerobic digestion of organic wastes (for example agricultural residues, animal manure, and domestic waste) by bacteria. The chief constituent of biogas is CH_4, but there is also CO_2, very small quantities of hydrogen sulfide (H_2S), nitrogen (N_2), and some other non-combustible gases. The percentage of methane is usually between 50% and 70%, and this proportion is the key element that specifies the calorific value of biogas.. Oxygen- and sulfur-containing compounds such as CO_2 and H_2S reduce the heating value of biogas; therefore, biogas purification processes, in which these components are removed, are preferred to increase energy efficiency. As a simple hydrocarbon, CH_4 can be used safely and efficiently as a fuel in internal combustion engines due to its chemical stability. In addition, the combustion of biogas reduces the amount of methane released into the atmosphere, creating a positive effect in terms of global warming, since methane has a much higher global warming potential than carbon dioxide. The disadvantages of biogas are limited by the low flame propagation speed inside the cylinder due to its low heating value and the low

volumetric efficiency resulting from the unburned mixture. Nevertheless, due to its high combustion characteristics, ease of production from renewable sources, and strong potential as an energy storage technology, biogas is considered a highly important energy source in today's energy markets (Yılmaz, Yavuz, & Gümüş, 2020).

2.7. Methane

Both hydrogen and methane, as alternative fuels, can provide remarkable advantages in efficiency and performance of internal combustion engines. Hydrogen being the lightest and most abundant element in the universe, basically generates just water vapor as a combustion product, therefore, it is an environmentally friendly source with zero carbon-based emissions. Methane, however, is the major component of natural gas.As a matter of fact, hydrogen has spectacular advantages because of its high heating value and very wide ignition limits whereas, the low flame speed of methane can cause some combustion problems. One of the major problems of backfiring is the low ignition energy of hydrogen which together with storage limitations, constitutes the main technical barriers for its widespread application. Generally, these fuels are envisaged in dual or ternary fuel systems with a fuel such as methanol to increase thermal efficiency and decrease emissions (Akbıyık, 2025).

Methane is the major constituent of natural gas and it contributes to good knock resistance and low particulate matter (PM) emissions because of its high octane number and hydrogen-to-carbon ratio. Hence, it is regarded as a clean fuel in terms of the emission performance. On the other hand, the methane molecule has a very stable structure, which results in a slow combustion rate and causes ignition difficulties when a lean mixture is used. The slow combustion leads to increased cycle-to-cycle variations, reduced thermal efficiency, and increased exhaust gas temperatures in spark-ignition engines. Still, methane, because of its high hydrogen content, makes possible a more environmentally friendly combustion process, hence the release of carbon emissions is lowered. To enhance engine performance and keep the combustion stable condition even with a low energy density, several methods like changing the ignition energy, multi-point ignition, and generating turbulent mixture formation are utilized (Chen et al., 2019).

3. Results and Discussions

3.1 Use of Liquefied Petroleum Gas and Compressed Natural Gas as Dual Fuels in Spark-Ignition Engines

Doğu et al. (Doğu, Yontar, & Kantaroğlu, 2018) first conducted tests using single fuel operation with gasoline (G100), and then compared the results by adding supplementary fuels. They injected 10% CNG (CNG10) and 5% LPG (LPG5) into gasoline on a mass basis. In their experimental study, they examined the effects on engine performance and exhaust emissions. The results indicated that both fuels caused a reduction in torque and volumetric efficiency compared to gasoline. For CNG10, torque decreased by 17.4% and volumetric efficiency by 23.2%, whereas for LPG5, torque decreased by 8.5% and volumetric efficiency by 15.6%. In terms of specific fuel consumption, both mixtures showed improvement compared to gasoline. A reduction of 5% was achieved for CNG10 and 7.1% for LPG5. Emission analysis showed significant decreases in CO and HC emissions for both fuels. HC emissions decreased by 29% for CNG10 and 34% for LPG5. However, both mixtures caused NOx emissions to increase by 4 to 5 times compared to gasoline.

Sayın et al. (Sayın, Çanakçı, & Kılıçaslan, 2005) examined the effects of combined use of gasoline and LPG on the performance and emissions of a dual-fuel engine. The results showed that specific fuel consumption in dual-fuel operation was lower than in single-fuel operation.

This improvement was attributed to increased turbulence in the intake manifold caused by high-pressure LPG injection, which enhances combustion efficiency. Exhaust emissions were also found to be lower compared to single-fuel operation across all engine loads and speeds.

3.2 Use of Hydrogen as a Dual Fuel in Spark-Ignition Engines

In a study investigating hydrogen addition, Batmaz (Batmaz, 2007) experimentally analyzed the effects of using hydrogen as an auxiliary fuel on the performance and emission parameters of spark-ignition engines. In his experimental setup, a single-cylinder, four-stroke engine was operated with hydrogen-enriched fuel without any modifications. Hydrogen was added at rates of 4%, 8%, and 12%. The findings showed that hydrogen addition improved the combustion characteristics of the engine and significantly reduced CO and HC emissions. It also resulted in lower specific fuel consumption. However, due to hydrogen's low density and high displacement volume, volumetric efficiency, engine torque, and power output decreased. Therefore, while hydrogen addition provides environmentally favorable emission benefits, it presents limiting effects on engine performance.

3.3 Use of Dimethyl Ether as a Dual Fuel in Spark-Ignition Engines

In the study where dimethyl ether (DME) was added to gasoline as a secondary fuel, the effects of DME–gasoline mixtures on CO emissions in spark-ignition engines were examined. The findings showed that DME improves combustion due to its oxygenated structure and significantly reduces CO emissions, particularly under lean-burn conditions. During cold-start operation, CO levels decreased more rapidly than with gasoline, which was attributed to DME entering the engine in gaseous form and forming a more homogeneous mixture. However, while certain proportions of DME addition reduced emissions, higher addition rates caused an increase in CO formation. It was also determined that injection strategy and ignition timing significantly affect emission outcomes. Overall, the study concluded that DME has strong potential for reducing CO emissions in gasoline engines when used as a supplementary fuel, but optimal effects require careful selection of blending ratio, combustion conditions, and injection strategy (Sezer, 2025).

3.4 Use of Acetylene Gas as a Dual Fuel in Spark-Ignition Engines

The experiment added 20% and 30% acetylene gas to gasoline at variable engine speeds and constant throttle position to study the effects on exhaust gas temperature and emission levels. The outcomes displayed substantial decreases: exhaust gas temperature diminished by 8–21%; HC emissions by 40–56%; CO emissions by 30–60%; CO_2 emissions by 25–55%; and NOx emissions by 5–19%. Nevertheless, the occurrence of knocking due to acetylene self-ignition at 3 bar pressure was noticed, which led to reduced combustion efficiency (Vural & Özer, 2014).

3.5. Use of Biodiesel as a Dual Fuel in Spark-Ignition Engines

Fil (Fil, 2025) conducted a study investigating the effects of gasoline–biodiesel fuel blends under partial load conditions and examined their performance and emission characteristics. In the study, tests were performed on a four-cylinder, multi-point injection engine using 100% gasoline (B100), 95% gasoline + 5% biodiesel (B95BD5), and 90% gasoline + 10% biodiesel (B90BD10) blends at different excess air ratios (λ = 0.9, 1.0, 1.1). The results showed that 5% biodiesel addition reduced brake-specific fuel consumption, increased volumetric efficiency, and decreased unburned hydrocarbons and carbon monoxide emissions. However, due to the high oxygen content of biodiesel, an increasing trend was observed in carbon dioxide and nitrogen oxide emissions. Under lean-burn conditions (λ = 1.1), the highest brake thermal efficiency was achieved with the 10% biodiesel blend. Overall, the study indicated that

biodiesel use in gasoline engines can provide significant reductions in harmful emissions without causing substantial performance losses, highlighting its notable potential.

4.Conclusions and Recommendations

In this study, the effects of different gaseous secondary fuels used in spark-ignition engines on engine performance and exhaust emissions were investigated and examined using the available literature. When the studies presented in the literature are generally evaluated, it is observed that the use of various alternative fuels and fuel additives in spark-ignition engines creates significant effects on both performance and emissions. The gases examined focus on the use of LPG, CNG, hydrogen, dimethyl ether, acetylene, biogas, and methane as additives to gasoline. The findings obtained from the literature review are as follows:

- In general, dual-fuel applications lead to limited reductions in engine performance, while providing significant improvements in emissions.
- In spark-ignition engines with the addition of Compressed Natural Gas (CNG) and LPG:
  - It has been determined that torque and volumetric efficiency decrease compared to gasoline.
  - On the other hand, a 5–7% improvement in specific fuel consumption was achieved, and significant reductions in CO and HC emissions were observed.
  - However, a 4–5-fold increase in NOx emissions was noted.
- When hydrogen is added, combustion characteristics improve, resulting in substantial reductions in CO and HC emissions and a decrease in specific fuel consumption. However, due to its low density, charging efficiency and engine torque also decrease.
- Dimethyl ether, being an oxygenated compound, increases combustion efficiency and particularly reduces CO emissions, providing a more homogeneous mixture under lean conditions. However, at high DME blending ratios, CO formation may increase again.
- In experiments with acetylene addition, significant reductions in HC, CO, CO_2, and NOx emissions were observed. However, due to its high flammability, the tendency for knocking increased, which adversely affected combustion efficiency.
- The addition of biodiesel, when used in small amounts, reduced brake-specific fuel consumption and lowered HC and CO emissions. However, due to its high oxygen content, an increasing tendency in CO_2 and NOx emissions was noted.

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LLM TABANLI YAPAY ZEKA AJANLARININ ETKİSİ: TEK VE ÇOKLU AJANLI YAPAY ZEKA YAPILARI ARASINDA DENEYSEL KARŞILAŞTIRMA

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ÖZET

Büyük Dil Modellerinin (LLM) verimliliğinin artması ve uygulama alanlarının genişlemesiyle birlikte, araştırma ilgisi son yıllarda temel dil modellerinden birleşik yapay zeka sistemlerine, oradan da daha karmaşık görevler için kullanılan çoklu ajan mimarilerine yönelmiştir. Bu sistemler, geliştirilmiş akıl yürütme yetenekleri, otonom karar verme becerileri ve görev odaklı çalışma yapısıyla birlikte, dil modellerinin temel sınırlılıklarından biri olan bağlam penceresi uzunluğu sorununu azaltmaktadır. Bu alana yönelik artan ilgiye rağmen, mevcut literatürde LLM tabanlı yapay zeka ajan sistemlerinin performansını sistematik olarak değerlendiren yeterli deneysel çalışma bulunmamaktadır. Özellikle bu sistemlerin verimliliği; ajanlar arası iş birliği, kullanılan modelin yetenekleri, görevlerin doğası, araçların kalitesi ve sistemin yapısı gibi birçok faktöre bağlıdır. Bu çalışmada, LLM tabanlı tek ajan ve çoklu ajan yapılarının, bir satın alma sürecinin otomasyonu görevi kapsamında deneysel olarak karşılaştırılması amaçlanmaktadır. Deney, Python diliyle Google Colab ortamında ve CrewAI çerçevesi kullanılarak gerçekleştirilmiş, performans takibi ise AgentOps platformu aracılığıyla yapılmıştır. Bu süreçte yürütme süresi, token tüketimi ve görev başarı oranı gibi ölçütler değerlendirilmiştir. Sonuçlar, her iki sistemin de görevi başarıyla tamamladığını, ancak beklentilerin aksine çoklu ajan sisteminin daha kısa yürütme süresi ve daha az token kullanımı sergilediğini göstermiştir. Bu bulgular, ajanlar arasındaki görev dağılımı ve iş birliğinin, basit görevlerde bile genel verimliliği artırabileceğini ve operasyonel maliyetleri azaltabileceğini göstermektedir. Dolayısıyla bu çalışma, yapay zeka sistemlerinin pratik tasarım yönlerini açıklığa kavuşturmakta ve ajan yapısı ile organizasyonunun etkisini ortaya koyan yeni bir deneysel karşılaştırma sunmaktadır.

Anahtar kelimeler: Büyük dil modeli (LLM), Tekli ajan, Çoklu ajan, Görev otomasyonu

THE IMPACT OF LLM-BASED AI AGENTS: EXPERIMENTAL COMPARISON BETWEEN SINGLE AND MULTI-AGENT AI STRUCTURES

ABSTRACT

With the increasing efficiency of large language models (LLMs) and the expansion of their applications, research attention has shifted from basic LLMs to compound AI systems, and, more recently, to multi-agent architectures for more complex tasks. These systems demonstrate enhanced reasoning capabilities, autonomous decision-making, and improved task focus while mitigating the limitations of the context window length, one of the main constraints on large language models. Although there has been growing interest in this field, the current literature still lacks a sufficient number of experimental studies that systematically evaluate the performance of LLM-based AI agent systems. This is especially true since their efficiency depends on several factors, including collaboration among agents, the efficiency of the employed model, the nature of the tasks, the quality of the tools, and the structure of the system. This study aims to experimentally compare LLM-based single-agent and multi-agent structures for automating a procurement process. The experiment was conducted using the CrewAI framework in the Google Colab environment with Python, and performance was tracked via the AgentOps platform to measure metrics execution time, token consumption, and task success rate. The results showed that both systems successfully completed the task. Unexpectedly, the multi-agent system exhibited a shorter execution time and lower token consumption. These findings suggest that role distribution and collaboration among agents can improve overall efficiency, even for simple tasks, and reduce operational costs. Therefore, this study contributes to clarifying practical aspects of AI system design and provides a novel experimental comparison demonstrating the impact of agent structure and organization.

Keywords: Large language model (LLM), Single agent, Multi agent, Task automation

1. Introduction

In recent years, Multi-Agent Systems (MAS) have received considerable attention for their capability to handle complex problems. These systems comprise autonomous entities known as agents, which are designed to perceive their environment, remember past situations, make decisions, and take actions (Perera et al., 2025). Agents cooperate, leveraging their knowledge and tools to make informed decisions and solve assigned tasks. Despite the efficiency of agent systems, they have faced several challenges, including learning, fault detection, task allocation, and generalization to new cases (Dorri et al., 2018).

Recent advances in Large Language Models (LLMs) represent a significant turning point in the history of artificial intelligence. LLMs exhibit broad capabilities in knowledge acquisition, reasoning, and interaction. LLMs have led to the development of LLM-based agent systems, which some researchers view as a step toward Artificial General Intelligence (AGI) (Xi et al., 2023). Unlike traditional rule-based systems, these systems rely on LLMs, which enable them to reason more effectively and to use their knowledge to handle long contexts and extract information more effectively (Zhao et al., 2024). These systems follow the ReAct principle, which involves reasoning and action. They comprise three key components: brain, perception, and action. The brain represents LLM and memory, whereas action depends on tools that enable agents to perform tasks (Xi et al., 2025). Current research often focuses on employing these systems to improve efficiency.

The efficiency of LLM-based agent systems depends on several factors, making it difficult to identify a single approach that yields optimal performance. Some of the most important factors include collaboration among agents, model efficiency, task characteristics, tool quality, and system structure. The context window problem, considered one of the primary limitations of LLMs, has been a key driver of the shift toward the use of multi-agent systems (Zhao et al., 2024). Recent studies have shown that allocating tasks and tools to each agent and establishing a clear distribution of roles in a multi-agent system generally lead to improved performance and efficiency by reducing task complexity and guiding models toward more effective reasoning (Li et al., 2025; Mohammed & Kora, 2025). Although LLM-based multi-agent AI systems are highly efficient, they may be more costly due to higher communication overhead between agents and frequent calls to tools and LLMs. The balance between cost and efficiency, as well as the choice between single-agent and multi-agent systems, remains an area of ongoing research. With advances in LLMs, single-agent systems have achieved performance comparable to that of multi-agent systems in less complex tasks, thereby reducing the need for multi-agent systems in many cases. Our study is motivated by this observation, as there are currently insufficient comparisons between single-agent and multi-agent systems for low-complexity tasks.

This study aims to perform an experimental comparison between LLM-based single and multi-agent structures within the task of automating a procurement process. The results showed that both systems successfully completed the task; however, unexpectedly, the multi-agent system recorded a shorter execution time and lower token consumption. These findings suggest that the distribution of roles and collaboration between agents can improve overall efficiency, even in simple tasks, and reduce operational costs. Therefore, this study contributes to clarifying the practical aspects of designing AI systems and provides a new experimental comparison that helps demonstrate the impact of agent structure and organization.

2. Related work

LLM-based AI agent systems are considered a new technology that emerged around 2022. Therefore, the literature remains limited. However, the field continues to grow significantly. This section reviews the major studies that have contributed to this field, with a focus on key concepts and practical applications.

Zhao et al. (2024) discussed the capabilities of LLMs and how they contribute to the development of multi-agent systems. Xi et al. (2025) conducted a comprehensive study on LLM-based agents, covering configuration frameworks, application scenarios, and future directions of LLM-based agents. There is also research that provides an overview of various applications of LLM-based multi-agent systems across different fields (Wang et al., 2024). From a practical perspective, Zhong et al. (2024) applied LLM-based agent systems to develop a framework for information processing in Internet of Things (IoT) environments, whereas Jiang et al. (2025) proposed a framework to enhance decision making in autonomous driving systems. In the field of networking, Chatzistefanidis et al. (2024) presented a framework for automating shared 6G networks and optimizing resource allocation among users. From a different perspective, Park et al. (2023) conducted simulations of human behavior using LLM-based multi-agent systems to examine their ability to interact in everyday human-like scenarios, raising questions about how well these systems can perform under full autonomy. Li et al. (2025) conducted an experimental comparison between single-agent and multi-agent systems for predicting Alzheimer's disease, demonstrating that multi-agent systems are more effective than single-agent systems. A survey conducted by X. Li et al. (2024) provides an overview of the key concepts, trends, and challenges in the development of LLM-based agent systems.

Despite the growing interest in this field, studies and experiments in other fields remain necessary. Cooperation among agents and their design structures, evaluation metrics, interactions with humans, and the autonomy and security of these solutions remain important research gaps.

3. Method

This section aims to explain the implementation of the experiment, the architectures used, the evaluation of system performance, and the experimental results.

3.1 Use case

The procurement process was selected as the use case for this experiment to compare the performance of single-agent and multi-agent systems. The process involves several steps: it begins with a request for a specific product, followed by generating search keywords and conducting online research to collect and scrape information about the product and its alternatives regarding specifications and prices. It concludes by comparing the options and generating a summary report. This case was chosen because it follows a clear and structured workflow, making it suitable for comparison of the two systems. In addition, most applied studies focus on coding or scientific research tasks; therefore, incorporating this use case expands the applications of LLM-based agent systems.

3.2 Agents and Structures

The number of agents is the primary variable compared in this study. A single-agent system, as its name suggests, consists of one agent performing all tasks, while a multi-agent system consists of four agents; the query generator agent, which generates search keywords required to search for products; the web search agent, which searches Google for products using those keywords; the product scraper agent, which scrapes product information from the web for each

product; and finally, the report generation agent, which analyzes the results and generates the final report. Figure 1 provides an overview of the agents within each architecture.

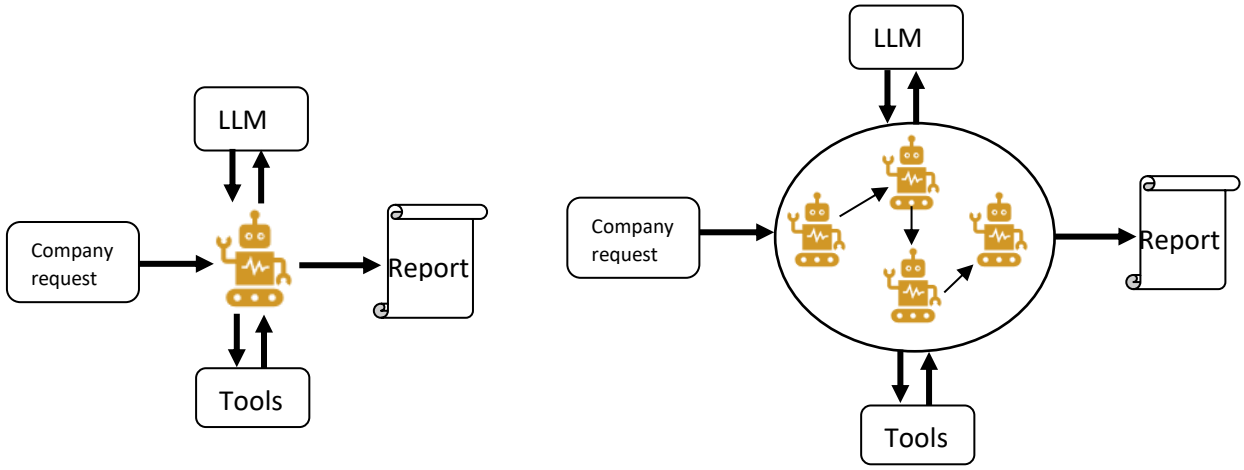

Figure 1. Overview of the single-agent (left) and multi-agent (right) system architectures.

3.3 Tasks and tools

The use case comprises four tasks, each assigned to a specific agent based on its role in the multi-agent system; in the single-agent system, a single agent performs all four tasks. The process is sequential, meaning tasks are performed in a specific order: generating search keywords, searching the internet using these keywords, scraping product information, comparing the results, and creating the final report. The agents leveraged the LLM's knowledge to generate search keywords and create the final report in HTML format, without the need for any additional tools or functions. For web searching and web scraping, two external tools were used: Tavily for searches and ScrapeGraph for web scraping, both of which were accessed via APIs. Figure 2 shows the sequence of tasks for the use case.

3.4 Experiment environment and conditions

The experiment was conducted using Google Colab and Python. CrewAI was selected as the framework for creating agent systems, and GPT 4.0 as the LLM. The processes were monitored using Agentops. The experimental conditions were designed to ensure fair results by keeping just one variable (agent counts) while all other conditions were kept the same. In other word the single-agent system included one agent, and the multi-agent system included four agents.

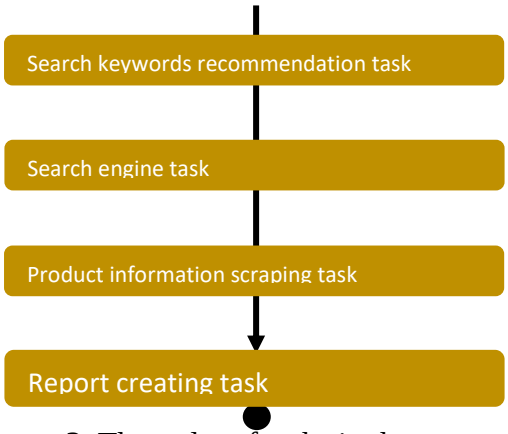

Figure 2. The order of tasks in the use case.

3.5 Evaluation metrics

The evaluation of LLM-based multi-agent systems remains a gap in current research. Currently, there is no general standard metric to evaluate the performance of these systems, as they rely on multiple components that work together. For this reason, evaluating only the system's outputs is insufficient; a deeper analysis of the agent's behavior is crucial to obtain a more reliable evaluation and to improve system efficiency. Most current studies focus on evaluating the system's final outputs, as in Mandal et al. (2025) and Wu et al. (2025). Common metrics include total token consumption and execution time, which are especially important for systems that require fast responses. Since many applications rely on performing automated tasks, the task success rate has become a key performance metric. Additional metrics can provide a deeper understanding of how the system works, such as the average task time or the rate of successful tool calls. In this study, execution time, total tokens, successful task rate, successful tool call rate, and average task time were used to evaluate system performance.

4. RESULTS

The experiment was conducted twice on each system using two different product requests. The variation between the two systems affected execution time and token consumption; however, the overall performance trends of the two systems were similar. Unexpectedly, the results showed that the multi-agent system achieved better efficiency in terms of execution time and resource consumption. Both systems completed the tasks successfully. Table 1 and Figure 3 present the results of the comparison between the two experiments. With respect to output quality, both systems generated the final report correctly, exhibiting proper structure and complete content. However, the report generated by the multi-agent system exhibited a more professional design and more formal phrasing.

Table 1. Performance comparison table between the single and multi-agent systems.

Experiment no	System Type	exec time (sec)	total tokens	successful tasks rate	successful tool calls rate	avg task time (sec)
1	Single-agent	149.357	82648	100%	100%	36.582
	Multi-agent	**75.360**	**27861**	**100%**	**100%**	**18.823**
2	Single-agent	57.064	56069	100%	100%	14.09
	Multi-agent	**54.917**	**33411**	**100%**	**100%**	**13.71**

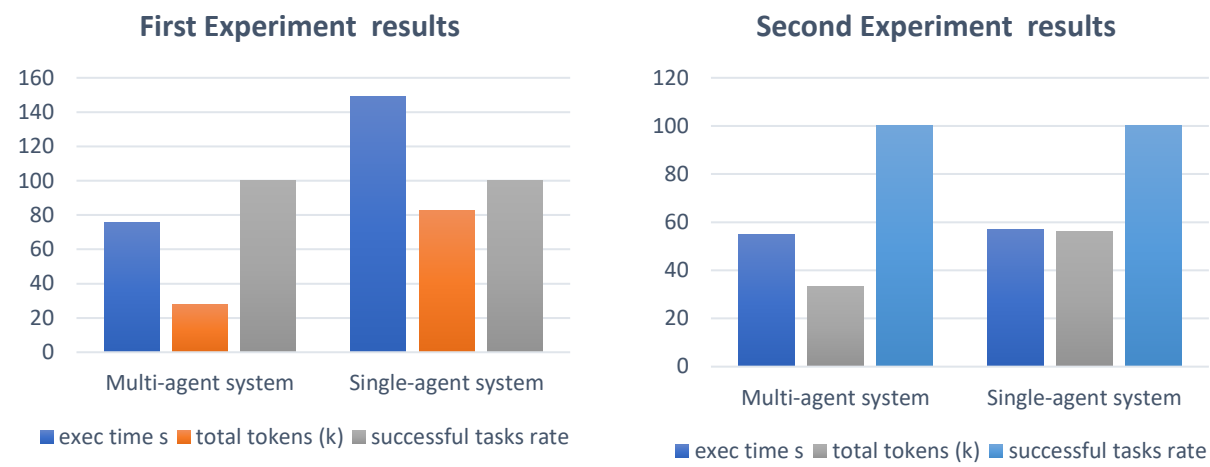

Figure 3. Performance comparison charts between the single and multi-agent systems.

5. conclusion

This study experimentally compared LLM-based single-agent and multi-agent systems in the context of automating a procurement process. The results show that both systems successfully completed the task. However, the multi-agent system exhibits reduced token consumption and a shorter execution time. This suggests that task sharing and cooperation between agents can positively impact system efficiency. The results demonstrate that multi-agent systems can offer cost and quality advantages not only in complex tasks but also in simpler scenarios.

6. Discussion and Future work

The results of this study cannot be generalized, as the performance of multi-agent systems depends on numerous factors, including the nature of the task, the type of process, the system's design structure, and the selection of the LLM. In our experiment, the process was sequential, which reduced the need for delegation and communication between agents. This may partially explain why the multi-agent system exhibited better token efficiency than the single-agent system. This study contributes to clarifying practical aspects of designing LLM-based agent systems and suggests directions for future work. One important direction is exploring how different communication methods and organizational structures impact the performance of agents. Another research topic is studying the level of autonomy at which these systems can operate safely and reliably. Human–agent interaction is also a key aspect that warrants study, alongside the development of more stable and fair evaluation metrics for assessing the performance of such systems across different tasks.

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ASKERÎ ARAÇLARDA BAKIM KADEMELERI VE EĞITIM DINAMIKLERI: KULLANICI, BIRLIK VE FABRIKA SEVIYESI YAKLAŞIMLARININ ANALIZI

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ÖZET

Bu çalışma, askerî taktik tekerlekli araçların hiyerarşik bakım yapısını incelemekte ve kullanıcı, birlik ve fabrika seviyelerindeki faaliyetlere odaklanmaktadır. Her bakım seviyesi; farklı teknik yetkinlikler, lojistik destek ihtiyaçları ve donanımlarla yürütülen, operasyonel sürekliliği ve araç göreve hazırlığını sağlayan bütünleşik bir sistemin parçasıdır. Bu çalışmada, bakım faaliyetlerinin yanı sıra, her seviyede yapılandırılmış teknik eğitimin rolü vurgulanmakta ve eğitim sonrası saha desteği ile kullanıcı geri bildirim mekanizmalarının sistem performansına olan katkısı analiz edilmektedir. Gerçek saha örnekleri üzerinden, uzaktan arıza tespiti ve geri bildirimle yapılan sistem iyileştirmeleri aracılığıyla, eğitimin yalnızca bir bilgi aktarımı değil; operasyonel sürdürülebilirliği destekleyen dinamik bir süreç olduğu ortaya konulmaktadır. Bulgular, teknik eğitim ile saha destek yapısının birlikte ele alınmasının, bakım sürecini statik bir işlem olmaktan çıkararak göreve uyumlu ve gelişime açık bir yapıya dönüştürdüğünü göstermektedir.

Anahtar Kelimeler: Eğitim ve lojistik destek, Saha destek sistemi, Entegre lojistik destek, Bakım personeli eğitimi

MAINTENANCE LEVELS AND TRAINING DYNAMICS IN MILITARY VEHICLES: ANALYSIS OF USER, UNIT, AND FACTORY-LEVEL APPROACHES

ABSTRACT

This study examines the hierarchical maintenance structure of military tactical wheeled vehicles, focusing on the user, unit, and factory-level operations. Each level involves distinct technical competencies, logistical support, and tools, forming an integrated framework to ensure operational continuity and vehicle readiness. Beyond maintenance tasks, this paper emphasizes the role of structured training at each level and analyzes how post-training support mechanisms and user feedback loops contribute to continuous improvement in system performance. Real-world examples, including remote troubleshooting and adaptation based on field experiences, illustrate how training evolves into a dynamic process influencing technical quality and operational sustainability. The findings highlight that technical training, coupled with active field support and systematic feedback evaluation, transforms maintenance from a static process into a responsive, evolving system aligned with mission requirements.

Keywords: Training and logistics support, Field support system, Integrated logistics support, Maintenance personnel training

1. Giriş

Zırhlı kara araçlarının yüksek teknolojiye sahip sistemlerinin operasyonel sürekliliği, planlı ve çok seviyeli bakım faaliyetlerine bağlıdır. Bu araçların bakım sistemleri, kullanıcı, birlik ve fabrika seviyeleri olmak üzere üç ana kategoriye ayrılmakta olup, her bir seviye farklı teknik bilgi, donanım ve lojistik altyapı gereksinimleri içermektedir. Bu makalede, bakım seviyelerinin teknik detayları, uygulama örnekleri ve kullanılan araç-gereçler kapsamlı şekilde incelenecek; çok katmanlı bakım sisteminin askerî operasyonlardaki önemi vurgulanacaktır.

2. Kullanıcı Seviyesi Bakım

2.1 Tanımı ve Kapsamı

Kullanıcı seviyesi bakım, askerî araçların günlük operasyonlarda kesintisiz ve güvenli şekilde görev yapabilmesi için, aracın doğrudan kullanıcı personel tarafından gerçekleştirilen temel bakım faaliyetlerini kapsar. Bu seviyedeki bakım işlemleri, rutin kontroller, temizlik, sıvı seviyelerinin izlenmesi ve küçük çaplı arızaların önlenmesi gibi basit fakat kritik görevlerden oluşur. Kullanıcı seviyesi bakım; görev öncesi, görev süresi ve görev sonrası olmak üzere periyodik olarak uygulanmakta olup, bakım zincirinin ilk halkasını oluşturur ve daha karmaşık tamirlerin önünü açar.
Örneğin, motor yağı, soğutma suyu, fren hidrolik seviyesi, lastik basıncı ve araç ışıklarının kontrolü kullanıcı seviyesi bakım kapsamındadır. Ayrıca görsel muayeneler aracın genel durumu hakkında ön bilgi sağlar ve sonraki bakım aşamalarına yönlendirme işlevi görür.

2.2 Uygulama Örnekleri

- Motor yağı ve soğutma suyu kontrolü: Sürücü, günlük göreve çıkmadan önce motor yağ ve soğutma suyu seviyelerini ölçer, eksiklik varsa tamamlar.
- Lastik basıncı ölçümü: Lastiklerin arazi şartlarına uygun hava basıncında tutulması, aracın güvenliği ve performansı için elzemdir. Basınç ölçümü manuel cihazlarla yapılır.
- Görsel muayene: Araç gövdesinde sızıntı, çatlak veya bağlantı gevşekliği gibi durumlar kontrol edilir.
- Fonksiyon testleri: Far, fren, sinyal ve haberleşme ekipmanlarının çalışırlığı test edilir.

2.3 Kullanılan Avadanlıklar

Kullanıcı seviyesinde kullanılan araç gereçler dayanıklı, portatif ve ergonomik olmalıdır:

- Tornavidalar (düz, yıldız), lokma anahtar setleri
- Lastik basınç ölçer ve el pompası
- Gres tabancası, yağlama fırçaları
- Basit elektrik test cihazları (kontrol lambası, voltmetre)
- Temizlik malzemeleri ve sıvı dolum hunisi

2.4 Personel Yeterliliği ve Eğitim

Bu seviyede bakım yapan personel temel teknik eğitim almakta, örneğin tank sürücüleri rutin bakım prosedürlerini öğrenip uygulamaktadır. Personel, bakım çizelgeleri doğrultusunda kontrol listelerini düzenli olarak tamamlamaktadır.

3. Birlik Seviyesi Bakım

3.1 Tanımı ve Kapsamı

Birlik seviyesi bakım, kullanıcı seviyesinde tespit edilen veya sahada ortaya çıkan daha karmaşık arızaların, birlik bünyesinde kurulan tamir atölyelerinde uzman personelce giderilmesini ifade eder. Bu bakım seviyesi, motor, şanzıman, elektronik kontrol üniteleri ve süspansiyon sistemleri gibi kritik bileşenlerde kapsamlı müdahaleler gerektirir. Birlik bakımının amacı, aracın operasyonel ortamdan çıkarılmaksızın, saha veya yakın lojistik merkezlerinde hızlı ve etkili onarımını sağlayarak operasyonel sürekliliği maksimize etmektir. Ayrıca, kritik parçaların performans ölçümleri, test ve ayarları da bu seviyede gerçekleştirilir.

3.2 Uygulama Örnekleri

- Motor onarımı: Performans düşüklüğü tespit edilen motor, atölyede sökülüp incelenir ve gerekli tamiratlar yapılır.
- Elektronik arıza teşhisi: Savaş yönetim sistemindeki sinyal kesintileri, bilgisayar destekli arıza teşhis cihazları ile analiz edilir.
- Şanzıman ve diferansiyel bakımı: Kritik hareket sistemleri sökülüp onarılır veya değiştirilir.
- Süspansiyon ve fren sistemi kontrolü: Ağır arazi koşullarına maruz kalan süspansiyon ve fren elemanları ayrıntılı olarak kontrol edilir.

3.3 Kullanılan Avadanlıklar

Birlik seviyesinde bakım için gelişmiş ekipmanlar kullanılır:

- Elektrikli ve pnömatik el aletleri (matkap, taşlama, vidalama)
- Hidrolik kaldırıcılar, krikolar
- Bilgisayar destekli arıza teşhis cihazları (multimetre, osiloskop, ECU programlayıcılar)
- Motor test ve kompresyon ölçüm cihazları
- Kaynak makineleri ve montaj ekipmanları

3.4 Personel Yeterliliği ve Organizasyon

Birlik seviyesi bakım personeli ileri teknik eğitimli teknisyenlerden oluşmakta, motor, elektronik ve mekanik alanlarda uzmanlaşmaktadır. Personel, bakım prosedürlerine uygun çalışmak ve lojistik destek ile koordinasyonu sağlamakla yükümlüdür.

4. Fabrika Seviyesi Bakım

4.1 Tanımı ve Kapsamı

Fabrika seviyesi bakım, askerî araçların yapısal ve fonksiyonel bütünlüğünü sağlamak üzere en kapsamlı ve ileri düzey bakım işlemlerini içermektedir. Genellikle üretim tesisleri veya yetkili bakım fabrikalarında gerçekleştirilir ve araçların kapsamlı revizyon, yenileme ve modernizasyon işlemlerini kapsar.
Bu seviyede motor ve şanzımanın komple revizyonu, elektronik sistemlerin yenilenmesi, gövde yapısının güçlendirilmesi ve zırh plakalarının değiştirilmesi gibi ileri teknoloji ve hassasiyet gerektiren işlemler yürütülür. Parçaların hassas ölçüm, test, kalibrasyon, kalite kontrol ve yazılım güncellemeleri de fabrika seviyesinde yapılır.

4.2 Uygulama Örnekleri

- Motor revizyonu: Motor tamamen sökülüp parçalar ölçülür, aşınan parçalar değiştirilir ve performans testlerine tabi tutulur.
- Elektronik sistem modernizasyonu: Yeni nesil yazılım ve donanımlar entegre edilir.
- Araç gövde yenileme: Zırh plakaları değiştirilir, korozyon önleyici kaplamalar uygulanır.
- Kapsamlı test ve sertifikasyon: Araçların hareket kabiliyeti, ateş gücü ve elektronik sistemleri fabrikada detaylıca test edilir.

4.3 Kullanılan Ekipmanlar

- Ağır kaldırma ve montaj makineleri
- CNC makineleri, hassas ölçüm cihazları
- Robotik kaynak sistemleri
- Gelişmiş elektronik test ve kalibrasyon cihazları
- Yazılım güncelleme ve simülasyon ortamları

4.4 Personel Yeterliliği ve Yönetim

Fabrika seviyesi bakım personeli mühendisler, yüksek eğitimli teknisyenler ve kalite kontrol uzmanlarından oluşur. Bu personel, ileri mühendislik bilgisi ile bakım süreçlerini uluslararası kalite standartlarına uygun şekilde yürütür.

5. Bakım Seviyeleri Arasındaki Entegrasyon ve Lojistik Önemi

Askerî araç bakım faaliyetlerinde bakım seviyeleri arasındaki entegrasyon, operasyonel etkinliği ve araçların görevde kalma süresini doğrudan etkileyen kritik bir unsurdur. Bakım süreçlerinin hiyerarşik yapısı, kullanıcı, birlik ve fabrika seviyelerinde yürütülen işlemlerin koordineli şekilde planlanmasını ve uygulanmasını gerektirir. Bu koordinasyonun sağlanması, bakım döngüsünün etkinliği, lojistik destek altyapısının yeterliliği ve personelin eğitim seviyesi ile yakından ilişkilidir.

5.1 Bakım Seviyeleri Arasındaki İlişki ve Süreç Yönetimi

Kullanıcı seviyesinde tespit edilen basit arızalar veya bakım ihtiyaçları, hızlı müdahaleyle giderilmediğinde veya teknik olarak aşılması gereken sorunlara dönüştüğünde, bu durum birlik seviyesine sevk edilir. Birlik seviyesi bakım merkezleri, kullanıcı seviyesinde çözülemeyen teknik problemleri çözerek, aracın operasyonel sürekliliğini sağlar ve fabrika seviyesine gitme ihtiyacını minimize eder. Ancak, birlik seviyesinde de giderilemeyen kapsamlı arızalar veya revizyon gereksinimleri fabrika seviyesine aktarılır.
Bu aşamalar arasındaki etkin bilgi akışı, bakım planlarının güncellenmesi ve operasyonel gereksinimlerin karşılanması bakımından önemlidir. Bakım kayıtları, arıza geçmişi ve performans verilerinin dijital ortamda paylaşılması, bakım kararlarının hızlı ve doğru verilmesini mümkün kılar.

5.2 Lojistik Zincirinin Rolü

Bakım faaliyetlerinin aksamaması için lojistik destek sisteminin sağlıklı işlemesi gerekmektedir. Her bakım seviyesi, ihtiyaç duyulan yedek parça, özel araç-gereç ve malzeme temininde farklı lojistik stratejileri gerektirir.

- Kullanıcı seviyesi bakımda, kritik olmayan ve standart yedek parçalar araç içinde veya birliklerin depolarında stoklanır. Bu sayede küçük bakım işlemleri hızlıca gerçekleştirilir.
- Birlik seviyesi bakımda, daha teknik ve kritik parçalar birliklerin bakım depolarından temin edilir. Ayrıca, uzman personel tarafından kullanılan özel ekipmanların da lojistiği koordineli şekilde yürütülür.
- Fabrika seviyesi bakımda, yüksek maliyetli ve hassas parçalar, üretici firmalardan veya merkezi depo ve lojistik merkezlerinden tedarik edilir. Bu aşamada lojistik, bakım sürelerinin uzamaması için etkin zaman yönetimi ve stok planlamasını zorunlu kılar.

Bu üç seviyede lojistik destek, bakım sürecinin zamanında ve etkin şekilde tamamlanmasını garanti eder ve operasyonel kesintilerin önüne geçer.

5.3 Bakım Planlaması ve Yönetimi

Bakım seviyeleri arasında entegrasyonu sağlayan en önemli unsur, kapsamlı bir bakım planlama ve yönetim sistemidir. Bu sistem, bakım faaliyetlerinin önceliklendirilmesini, kaynakların optimal kullanılmasını ve süreçlerin standardizasyonunu hedefler.
Modern bakım yönetimi yazılımları, araçların arıza verilerini gerçek zamanlı izleyerek, bakım ihtiyaçlarını öngörür ve planlamayı kolaylaştırır. Böylece, hem kullanıcı hem birlik hem de fabrika seviyesindeki bakım süreçleri senkronize edilir, gereksiz tamir veya parça değişimlerinin önüne geçilir.

5.4 Personel Eğitimi ve İletişimi

Bakım seviyeleri arasındaki koordinasyonun başarısı, sadece teknik altyapıya değil, aynı zamanda personelin eğitim ve iletişim becerilerine bağlıdır. Kullanıcı seviyesindeki personelin arızaları doğru tespit edip ilgili seviyelere bildirmesi, birlik ve fabrika bakım ekiplerinin etkili müdahalesinin ön koşuludur.
Düzenli eğitim programları ve bakım prosedürlerine yönelik seminerler, bakım zincirindeki tüm personelin bilgi ve becerilerinin güncel tutulmasını sağlar. Aynı zamanda dijital iletişim ve raporlama araçlarının kullanımı, bakım seviyeleri arasında zaman kaybını en aza indirir.

5.5 Operasyonel ve Ekonomik Kazanımlar

Bakım seviyeleri arasındaki etkin entegrasyon, sadece teknik başarı sağlamaz; aynı zamanda operasyonel etkinlik ve ekonomik açıdan da önemli kazanımlar yaratır. Bakım süresinin kısalması, aracın görev dışı kalma süresinin azalmasına ve dolayısıyla operasyonel gücün artmasına yol açar. Ayrıca, lojistik ve bakım maliyetleri düşürülür, parça ve işçilik kaynaklarının verimli kullanımı sağlanır.
Bu bağlamda, bakım sisteminin sürekli iyileştirilmesi, teknolojik gelişmelerin entegrasyonu ve veri analizlerine dayalı karar mekanizmaları kritik önem taşır.

6.1 Eğitim ve Personel Gelişimi: Bakım Sürekliliğinin Temel Unsuru

Askerî araç bakım sistemlerinin başarısı yalnızca ekipman temini ve süreç planlamasına değil, doğrudan bu sistemleri uygulayan personelin bilgi ve beceri düzeyine bağlıdır. Kullanıcı, birlik ve fabrika seviyelerindeki bakım faaliyetlerinin sürdürülebilirliği; her seviyede görev yapan personelin ihtiyaca uygun, sistematik ve teknik olarak güncel eğitimler almasını gerektirir. Bu nedenle eğitim süreçleri, bakım sisteminin ayrılmaz bir bileşeni olarak değerlendirilmelidir.

6.1.1 Kullanıcı Seviyesi Eğitimler

Kullanıcı seviyesi eğitimler, genellikle aracın operatörleri ve sürücüleri için düzenlenmektedir. Bu eğitimlerin temel amacı; aracın doğru ve güvenli şekilde kullanılmasını, basit arızaların

tanımlanmasını ve günlük bakım faaliyetlerinin eksiksiz şekilde yerine getirilmesini sağlamaktır. Eğitim içerikleri genellikle şunları kapsar:

Araca günlük bakım ve kontrol listesi uygulaması

Sıvı seviyeleri (yağ, soğutma suyu, fren hidroliği) kontrolü

Hava filtresi, lastik basınçları ve dış aksam kontrolleri

Uyarı lambalarının takibi ve ön tanı koyma becerileri

Kullanıcı el kitabı ve temel teknik doküman okuma yetkinliği

Bu eğitimler çoğunlukla saha ortamında, araca doğrudan uygulama yapılacak şekilde verilir. Pratik temelli olduğu için öğrenme kalıcılığı yüksektir.

6.1.2 Birlik Seviyesi Eğitimler

Birlik seviyesi bakım, daha teknik detaylara hâkim personel tarafından gerçekleştirilir. Bu nedenle eğitim içeriği de daha kapsamlıdır. Eğitilen personel genellikle bakım çavuşları, teknisyenler ve araç sorumlularıdır. Bu seviyedeki eğitimlerin ana başlıkları şunlardır:

Elektriksel sistemlerin temel ölçüm ve test yöntemleri

Motor ve şanzıman arıza teşhis teknikleri

Elektronik kontrol üniteleri (ECU) arıza kodlarının okunması ve yorumlanması

Hızlı parça değişimi (starter, alternatör, akü vb.)

Diagnostik cihaz ve test yazılımlarının kullanımı

Bu eğitimlerde katılımcılar, hem teorik derslere katılır hem de uygulama araçları üzerinde birebir arıza giderme faaliyetleri yürütür.

6.1.3 Fabrika Seviyesi Eğitimler

Fabrika seviyesinde bakım yapan personel, genellikle yüksek teknik yeterliliğe sahip mühendis ve teknisyenlerden oluşur. Eğitimler daha çok sistem mühendisliği ve kalite süreçlerine odaklanır. Fabrika seviyesi eğitimlerin içeriği şu başlıkları içerebilir:

Komple sistem sökme ve montaj prosedürleri

Yazılım güncelleme ve elektronik bileşen kalibrasyonu

Tahribatsız muayene ve test yöntemleri (X-Ray, ultrasonik vb.)

Ar-Ge destekli teknik güncellemeler ve modernizasyon bilgisi

Fabrika kabul testleri (FAT) ve raporlama metodolojisi

Bu eğitimlerin büyük kısmı teknik dokümantasyon, laboratuvar ortamı ve yüksek teknoloji test altyapıları ile desteklenir. Katılımcılar detaylı teknik analiz ve geribildirim süreçlerine dahil edilir.

6.1.4 Eğitim Sonrası Saha Desteği ve Uygulama Etkisi

Eğitim faaliyetlerinin etkisi yalnızca sınıf ortamında ya da simülasyon üzerinden ölçülemez. Gerçek başarı, personelin sahadaki görevlerinde eğitimin etkisini sürdürebilmesi ve ihtiyaç duyduğunda destek alabilmesiyle mümkün olur.

Eğitmen olarak görev yapan kişi, bu bilinçle yalnızca eğitim anlarında değil, sonrasında da kursiyerlerle iletişimini sürdürmektedir. Eğitim alan personelin sahadaki karşılaştığı

beklenmedik teknik sorunlar, hızlı müdahale ve yönlendirme sayesinde çözüme kavuşturulmaktadır. Bu yaklaşım, sadece teknik destek değil; aynı zamanda kullanıcı nezdinde kurumsal güvenin pekişmesini de sağlar.

Gerçek bir örnek olarak, yurt dışında görev yapan bir kursiyer, resmi tatil günü bir sistemin devreye alınamaması nedeniyle doğrudan eğitmeni aramıştır. Telefon görüşmesi sırasında yapılan teknik yönlendirmeyle sorun hızlıca tespit edilmiş, gerekli müdahale gerçekleştirilmiş ve personel görevine kesintisiz şekilde devam etmiştir. Bu olay, eğitimin sahaya yansıyan etkisini ve eğitmen–kursiyer arasındaki güçlü iletişimin kritik önemini açıkça ortaya koymaktadır.

Ayrıca, eğitim sonrasında kursiyerlerden gelen geri bildirimler düzenli olarak kayıt altına alınmakta ve ortaklaşan şikâyet veya talepler teknik toplantılara taşınmaktadır. Bu sayede, eğitim yalnızca bilgi aktarımı değil; aynı zamanda araçların saha performansını artırmaya yönelik bir iyileştirme mekanizmasına dönüşmektedir. Toplantı sonuçlarına göre gerekirse araç tasarımında değişiklik yapılmakta veya kalite kontrol süreçleri daha sıkı hale getirilmektedir.

Eğitmenin sahada sürdürdüğü bu ilişki yalnızca bireysel destekle sınırlı kalmamaktadır. Farklı birliklerden ve görev bölgelerinden gelen benzer sorunlar ve kullanıcı talepleri zaman içerisinde sınıflandırılarak teknik ekiplerle paylaşılmakta, bu doğrultuda araç tasarımında iyileştirmeye yönelik değişiklikler yapılabilmektedir. Aynı şekilde, kalite kontrol aşamalarında sıklık artırımı ya da test prosedürlerinde detaylandırma gibi adımlar da kullanıcı geri bildirimlerine bağlı olarak uygulanmaktadır. Böylece eğitim süreçleri, yalnızca bilgi aktarımı değil; aynı zamanda ürün geliştirme ve operasyonel mükemmellik için bir veri kaynağı işlevi görmektedir.

Tüm bakım seviyelerinin etkin işlemesi için eğitim kritik bir faktördür. Personelin görevini bilinçli ve doğru biçimde yerine getirebilmesi, bakım sürekliliğinin temelini oluşturur. Ayrıca sistematik eğitimler sayesinde arıza tespiti ve müdahale süresi azalır, yedek parça kullanımı optimize edilir. Sahada doğrudan verilen uygulamalı eğitimler, teorik bilginin pratiğe dönüşmesini sağlar. Bu kapsamda bugüne dek eğitim verilen yaklaşık 300 personelin hiçbirinin araçla ilgili bir kazaya karışmamış olması, eğitimin doğrudan güvenlik performansına etkisini net biçimde ortaya koymaktadır.

Sonuç olarak, askerî bakım sisteminin başarısı yalnızca lojistik zincire değil; bu zinciri işleten personelin bilgi altyapısına da bağlıdır. Eğitimlerin sistematik ve seviyelere göre yapılandırılması, bakım sürekliliğinin en önemli güvencesidir. Dolayısıyla, eğitim planlaması bakım yönetiminin ayrılmaz bir parçası olarak ele alınmalıdır.

Uluslararası literatür de, teknik eğitimlerin yalnızca bilgi aktarımıyla sınırlı kalmadığını; aynı zamanda iş güvenliği performansına doğrudan etki edebildiğini ortaya koymaktadır. Örneğin Robson ve arkadaşlarının yaptığı kapsamlı derlemede, iş sağlığı güvenliği eğitimlerinin çalışanların bilgi ve davranışlarını anlamlı şekilde geliştirdiği, buna paralel olarak kaza oranlarının da azaldığı rapor edilmiştir. Burke ve arkadaşları tarafından yürütülen bir meta-analiz, eğitim yoğunluğu ve uygulamalı öğrenme unsurlarının kazaları azaltma üzerinde doğrudan etkili olduğunu göstermektedir. Casteel'in genç işçiler üzerinde yaptığı araştırmada, hedeflenmiş eğitim programlarının iş kazası kaynaklı tazminat taleplerini %42'ye kadar azalttığı belirlenmiştir. Benzer şekilde, sürücü odaklı güvenlik eğitimlerine ilişkin uluslararası çalışmalar, özellikle askeri ve ağır vasıta alanında eğitim alan personelin kaza sıklığında kayda değer düşüşler sağlandığını göstermektedir. Bu bağlamda, sahada eğitim verilen yaklaşık 300 personelde bugüne dek kaza yaşanmamış olması, yalnızca yerel bir başarı göstergesi değil, aynı zamanda literatürle uyumlu küresel bir eğilimin pratik yansımasıdır.

6. Sonuç

Askerî araçların operasyonel sürekliliği ve yüksek görev hazır bulunuşluk seviyesinin sağlanması, çok katmanlı ve hiyerarşik bir bakım sistemine dayanmaktadır. Bu sistem içerisinde kullanıcı, birlik ve fabrika seviyeleri bakım faaliyetleri, farklı bilgi birikimi, teknik donanım ve lojistik destek gereksinimleriyle ayrışmakla birlikte, birbirini tamamlayan ve bütünleşik bir yapı arz etmektedir.

Kullanıcı seviyesi bakım, aracın günlük operasyonlara hazır hale getirilmesi için temel kontrollerin, rutin sıvı tamamlamalarının ve küçük müdahalelerin uygulandığı kritik bir aşamadır. Bu seviyede yapılan bakım işlemleri, görev öncesi arızaların tespit edilmesini ve önleyici tedbirlerin alınmasını mümkün kılarak, operasyonel kesintilerin minimize edilmesini sağlar. Zırhlı kara araçları bağlamında değerlendirildiğinde, sürücülerin gerçekleştirdiği lastik basıncı ölçümü, motor yağı ve soğutma suyu kontrolü gibi işlemler, aracın arazi koşullarında güvenli ve etkin kullanılabilirliğini doğrudan etkiler. Kullanıcı seviyesinde kullanılan el aletlerinin ergonomik, dayanıklı ve kolay taşınabilir olması, bakımın hızlı ve etkin yapılabilmesi açısından vazgeçilmezdir.

Birlik seviyesi bakım, teknik donanım ve uzman personel gerektiren ara müdahale seviyesi olup, motor, şanzıman ve elektronik sistemler gibi kritik bileşenlerin onarım ve teşhis faaliyetlerini kapsar. Bu bakım aşaması, araçların arazi dışına çıkarılmadan saha ortamında onarılmasına olanak vererek, operasyonel sürekliliği artırır. Örneğin, zırhlı araçların elektronik kontrol ünitelerinde meydana gelen arızaların bilgisayar destekli arıza tespiti ve tamiri, birlik seviyesi bakımın temel faaliyetlerindendir. Ayrıca, bu seviyede kullanılan gelişmiş el aletleri ve test cihazları, bakım kalitesini artırırken, personelin yüksek teknik bilgi ve deneyim gereksinimi, eğitim programlarının önemini vurgular.

Fabrika seviyesi bakım ise, araçların revizyon, modernizasyon ve kapsamlı onarım işlemlerinin yapıldığı en üst seviyedir. Bu seviyede gerçekleştirilen motor revizyonu, elektronik sistem yenileme ve gövde kaplama işlemleri, aracın uzun vadeli performans ve dayanıklılığını garanti altına alır. Zırhlı kara araçlarının teknoloji ve fonksiyonlarının güncel tutulması, bu bakım seviyesinin sorumluluk alanına girmektedir. Fabrika seviyesinde kullanılan ileri teknoloji ekipmanlar ve yüksek uzmanlık gerektiren personel, bakım faaliyetlerinin kalite standartlarına uygun biçimde yürütülmesini sağlar.

Sonuç olarak, askerî bakım sisteminin başarısı yalnızca lojistik zincire değil; bu zinciri işleten personelin bilgi altyapısına da bağlıdır. Eğitimlerin sistematik ve seviyelere göre yapılandırılması, bakım sürekliliğinin en önemli güvencesidir. Dolayısıyla, eğitim planlaması bakım yönetiminin ayrılmaz bir parçası olarak ele alınmalıdır. Buna ek olarak, eğitimlerin saha desteğiyle sürdürülebilir hâle getirilmesi ve kursiyerlerden gelen geri bildirimlerin sistematik biçimde değerlendirilerek araç tasarımına ya da kalite süreçlerine yansıtılması, askerî araç yönetiminde operasyonel etkinliği artıran önemli bir faktördür.

Eğitim yalnızca bilgi aktarımı değil; aynı zamanda kullanıcı deneyiminden beslenen dinamik bir geliştirme mekanizması olarak da değerlendirilmelidir. Eğitimlerin sistematik ve seviyelere göre yapılandırılması, bakım sürekliliğinin en önemli güvencesidir. Dolayısıyla, eğitim planlaması bakım yönetiminin ayrılmaz bir parçası olarak ele alınmalıdır.

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EXPLORING MAGNETIC PROPERTIES of $GdCo_2$ THIN FILM

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ABSTRACT

A large class of very desirable materials that have recently garnered considerable interest in cutting-edge technology are intermetallic complexes, which consist of transition metals and rare earth elements. Since these compounds are anisotropic and can have their particle size easily adjusted, they exhibit excellent electrical, magnetic, and magneto-optical characteristics. They find widespread application in the production of permanent magnets and magneto-optical storage systems due to their extraordinary properties. This keeps people interested in learning more about this field. At room temperature, an amorphous GdCo2 thin film was made on Si(100) substrates. This film had unique structural and magnetic properties that are common in amorphous rare-earth transition metal systems. At a thickness of 100 nm, a significant transition in magnetic anisotropy was observed, characterised by a pronounced deviation in the orientation of the easy axis from that of the hard axis, accompanied by corresponding changes in remanence and coercivity values. We used a vibrating sample magnetometer (VSM), the anomalous Hall effect (AHE) and magneto-optical Kerr effect measurements (MOKE) to look at the magnetic properties and find out the magnetic saturation, coercivity, and remanence. The magnetic characteristics suggest that GdCo2 systems have potential for spintronic and magneto-optical applications; nevertheless, thorough characterisation under various processing conditions is essential for technical implementation. According to the findings, when subjected to a perpendicular magnetic field, the 100 nm film's Hall resistivity was found to be 0.575 μΩ·cm/(μB/f.u.). This anisotropy is very important for technology because it controls the stability and tunability of magnetisation, which has a direct effect on how well materials work in spintronic devices and magnetic storage systems.

Keywords: $GdCo_2$, Vibrating Sample Magnetometer, Magnetic Properties, Rare Earth Elements

INTRODUCTION

Transition-metal intermetallic compounds incorporating rare-earth elements (REE) constitute an intriguing class of functional materials that have gained considerable interest for modern technological applications. Their exceptional electrical, magnetic, and magneto-optical behaviors originate from their strong anisotropy and tunable particle size, making them highly versatile. Owing to these superior features, such materials have been widely employed in the fabrication of high-performance permanent magnets and magneto-optical data storage devices, thereby sustaining strong research momentum in this area [1].

Within this group, $GdCo_2$ alloys stand out as particularly compelling due to their distinctive ferrimagnetic nature and high degree of spin polarization. This substantial spin polarization is a key enabler for spintronic technologies, which exploit both the electronic charge and spin for information transfer and processing. The rapid evolution of spintronics has transformed the landscape of electronic device engineering, enabling systems with enhanced functionality, improved energy efficiency, and reduced power consumption [2].

The strong inherent spin polarisation of $GdCo_2$-based systems is a major advantage for magnetic sensing devices, which rely on being sensitive to small changes in magnetic fields. The elevated magnetic susceptibility and enhanced magnetisation fluctuations in amorphous $GdCo_2$ films at low applied fields render them more advantageous than crystalline $GdCo_2$ films, hence augmenting their practical applications. Nevertheless, considerable challenges in characterising $GdCo_k$ come from its ferrimagnetic behaviour. Conventional magnetometry techniques may lack the sensitivity required to detect domain dynamics and minor magnetic transitions near the compensation temperature, at which point the net magnetisation approaches zero [3].

Fortunately, vibrating sample magnetometer (VSM) offer elegant solutions to magnetic characterization challenges. VSM provides a precise and efficient approach for the magnetic characterization of materials, offering high sensitivity, broad measurement ranges, and rapid data acquisition. Based on the principle of detecting the magnetic moment induced in a sample that is mechanically vibrated within a uniform magnetic field, VSM enables direct and accurate determination of key magnetic parameters such as saturation magnetization (M_S), coercivity (H_C), and remanent magnetization (M_R). It is well-suited for both bulk materials and thin films, and when equipped with temperature-controlled measurement capabilities, VSM becomes a powerful tool for studying magnetic phase transitions, thermal effects, and magnetization dynamics. Its fast measurement capability and high repeatability make it particularly valuable for correlating synthesis conditions with magnetic behavior, enabling efficient material optimization. With these advantages, VSM serves as an indispensable characterization technique for the development of advanced magnetic materials, especially in emerging fields such as spintronics, magnetic semiconductors, and neuromorphic magnonic devices.

However, $GdCo_2$ ferrimagnetic compounds present distinctive characterisation issues. When temperatures go over certain limits, magnetisation values drop to very low levels, making it hard to do normal magnetometry observations. This constraint necessitates the exploration of alternate characterisation approaches that demonstrate increased sensitivity to subtle magnetic fluctuations [3]. Fortunately, the anomalous Hall effect (AHE) and magneto-optical Kerr effect measurements (MOKE) provide advanced characterisation solutions. Unlike regular magnetometers, these methods can find differences in magnetisation without needing the whole magnetic moment. The AHE is affected by conduction band polarisation, while the Kerr effect is controlled by optical transitions between sub-bands. These two effects give us different ways to look at the material's magnetic characteristics.

The AHE is an essential physical phenomenon used to investigate charge transport properties in solid-state materials. The Hall coefficient (R_h) reveals whether electrons or holes dominate conduction, while the magnitude of the Hall voltage allows for the calculation of carrier concentration and mobility, making Hall measurements a standard technique for semiconductor analysis. Beyond conventional systems, the Hall effect also holds significant relevance in magnetic materials. In ferromagnetic or ferrimagnetic thin films, an additional contribution known as the Anomalous Hall Effect (AHE) arises due to spin–orbit coupling and magnetization. This effect provides valuable insight into magnetic ordering, spin-dependent transport, and electron–spin interactions, making Hall measurements a powerful tool for emerging spintronics research. Because of its ability to correlate electrical and magnetic properties, the Hall effect is widely used in the characterization of magnetic thin films, sensors, and next-generation spintronic materials. Its simplicity, sensitivity, and diagnostic value make it indispensable for understanding and optimizing materials for magnetic sensing, data storage, and neuromorphic computing technologies.

In this work, we conduct an in-depth investigation of the structural and magnetic characteristics of $GdCo_2$ thin films through state-of-the-art characterization techniques. Leveraging these advanced methods enables us to gain valuable insights into their potential for high-performance spintronic and magnetic applications, paving the way for future technological advancements.

EXPERIMENTAL

This research employed DC magnetron sputtering utilising a stoichiometric $GdCo_2$ alloy target to fabricate an amorphous $GdCo_2$ thin film on a Si(100) substrate, achieving a thickness of 100 nm. To make sure the plasma environment was ideal and to keep impurities from getting in, the sputtering medium was high-purity argon gas (6N) held at a working pressure of $2x10^{-3}$ mTorr. The substrate was spun at 10 rpm while the film was being deposited to make sure that it developed evenly and that the composition of the surface stayed the same. We used a VSM to measure the temperature dependent magnetic properties between 50-430 K range, the AHE measurements in plane and out-of-plane directions under +-50 Oe range and magneto-optical Kerr effect measurements (MOKE) up to +-9 T to look at the magnetic properties and find out the magnetic saturation, coercivity, and remanence.

RESULTS and DISCUSSION

Figure 1 illustrates the **temperature dependent magnetisation measurement (M-T)** of the $GdCo_2$ thin film deposited at a thickness of 100 nm on the Si(100) substrate under room-temperature conditions. The M–T curve measured in the 50–430 K range for the 100 nm-thick $GdCo_2$ thin film. The inset displays the dM/dT versus temperature plot, representing the derivative of magnetization with respect to temperature. The minimum point in this derivative curve was identified as the Curie temperature (T_C) of the film, which was determined to be 383 K. The obtained Curie temperature is consistent with the values reported in the literature [2] and aligns with the results. This result indicates that the magnetic structure of the produced thin films matches the expected parameters and exhibits the desired thermal magnetic stability for practical applications.

The deposited $GdCo_2$ thin film can be classified as amorphous, a structural feature commonly observed in rare-earth-transition-metal thin films grown at room temperature due to restricted surface diffusion and low adatom mobility, which suppress crystalline ordering. This amorphous nature is consistent with the magnetic behavior observed in the VSM measurements. The smooth and isotropic magnetic response reflected in the M-T curve, along with the well-defined Curie temperature of 383 K, indicates a uniform magnetic phase without crystalline

anisotropy-driven anomalies. Such structural homogeneity is particularly beneficial for magneto-optical and spintronic applications, as amorphous films typically provide isotropic magnetization, smoother interfaces, and minimized grain-boundary scattering, collectively contributing to enhanced device performance and operational stability.

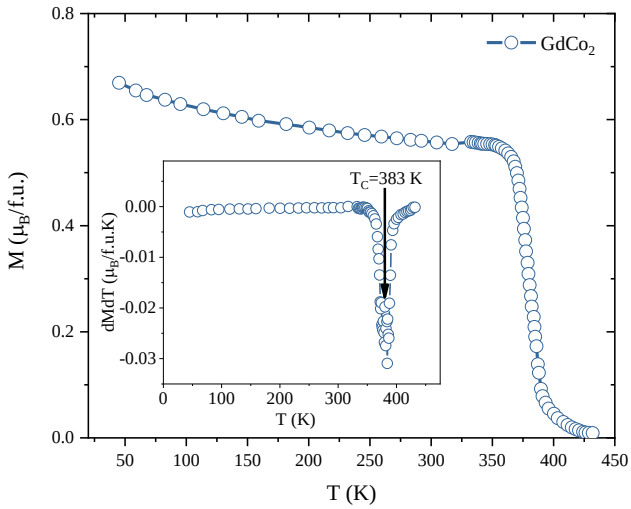

Figure 1. M-T measurement of $GdCo_2$

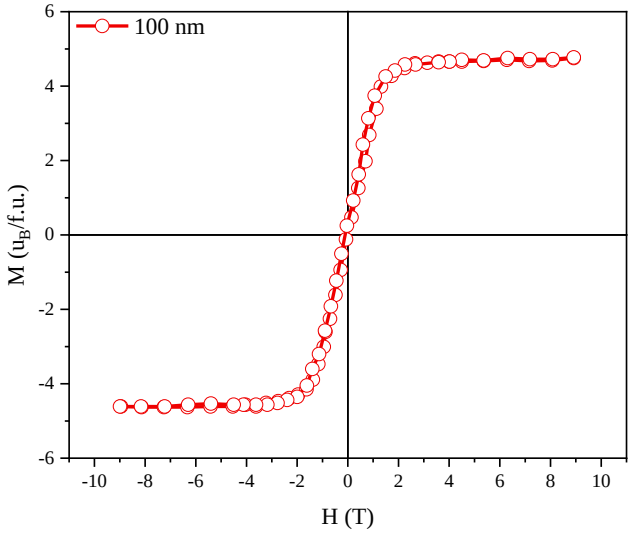

Figure 2. MOKE measurement of $GdCo_2$

According to the MOKE results in Figure 2, the measurements were conducted on the thin films produced at a sputtering pressure of 5 mTorr and a sputtering power of 50 W with thicknesses of 100, as this films exhibited superior soft magnetic behavior and lower coercivity. The saturation magnetization values of these soft magnetic films, which rapidly reach saturation, were found to be 4.5–5 μB/f.u. (850–950 emu/cc). These values are in good agreement with both the literature and the target values defined in the project proposal [1].

Therefore, to resolve the magnetic anisotropy behaviour of the system, the AHE measurements were carried out in Fig. 3(a) and (b). The measurements confirm the $GdCo_2$ thin film show good in-plane and out-of-plane magnetic anisotropy. Thin films were measured according to IP (0 °) and OOP (90 °) planes. Measurements performed for each axis are normalized within themselves to unveil the magnetic properties of thin films. Based on the obtained results, the Hall resistivity value for the 100 nm film was measured as 0.575 μΩ·cm/(μB/f.u.) under a

perpendicular magnetic field. This outcome is in good agreement with both the project's target values and the literature [3].

The magnetic response that relies on the axis reveals how the magnetoelastic effects, local atomic configurations, and exchange connections of amorphous rare-earth transition metal alloys are all fighting for attention. The transition from soft magnetic properties, marked by low coercivity and high permeability, to hard magnetic properties, indicated by increased HC along the hard axis, signifies a gradual transformation of the thin film when the direction of magnetisation reversal is less advantageous. This anisotropy has a direct effect on how well materials work in spintronic devices, magnetic storage technologies, and magnetic applications. This is important from a technological point of view because it affects the stability and tunability of magnetisation [4].

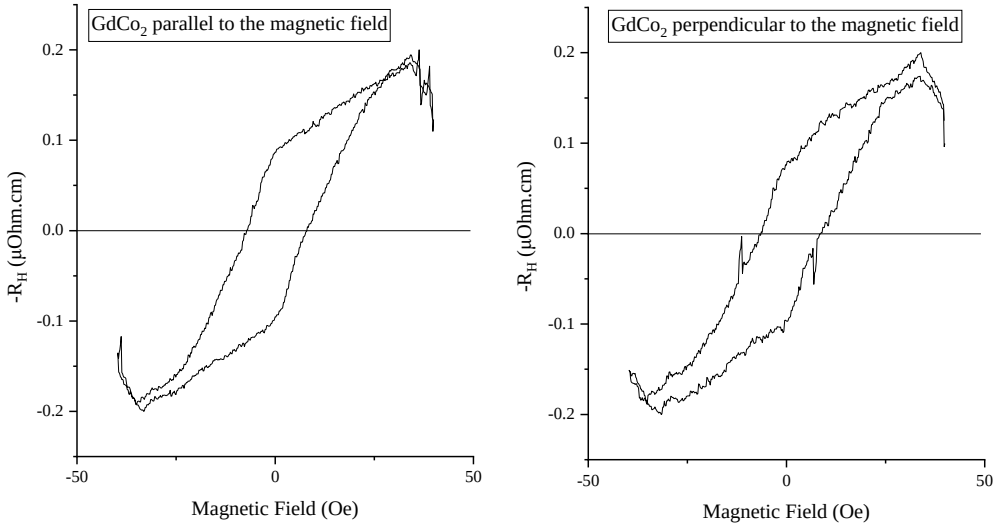

Figure 3. Hall effect measurement of $GdCo_2$ (a) 0 degree and (b) 90 degree

CONCLUSION

A thin layer of GdCo2 was generated at temperatures near room temperature using a Si(100) substrate for this discussion. Our sample exhibited all the characteristic magnetic and structural features of amorphous $GdCo_2$ systems. At a 100 nm thickness, there is a slight misalignment between the IP magnetic axis and the OOP axis in a thin layer. Sends resistivity signal only in out-of-phase direction. It is necessary to conduct research and categorise $GdCo_2$ systems before considering them as potentially highly beneficial magnetic materials with spintronic capabilities for the creation of novel optical media.

ACKNOWLEDGMENT

This study was supported by Scientific and Technological Research Council of Türkiye (TUBITAK) under the Grant Number 223M517.

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ZIRH ÇELİKLERİNDE LAZER KESİMİN MEKANİK ETKİSİ

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ÖZET

Savunma sanayii günümüzde en hızlı gelişen sektörlerden biridir ve zırhlı muharebe araçları bu alanda önemli bir yer tutmaktadır. Bu araçların üretiminde çelik, alüminyum, seramik ve kompozit malzemeler kullanılmakla birlikte, şekillendirilebilirlik, tedarik kolaylığı ve maliyet açısından en yaygın tercih edilen malzeme çeliktir. Zırh çelikleri, bu araçların tasarımlarına uygun geometrilerde kullanılmak üzere çoğunlukla lazer kesim yöntemi ile işlenmektedir. Ancak bu yöntemde malzeme yüzeyine aktarılan yüksek ısı girdisi, martensitik yapıya sahip yüksek sertlikteki çeliklerde mikroyapısal dönüşümlere ve buna bağlı olarak mekanik özelliklerde değişimlere yol açabilmektedir. Literatürde özellikle 600 HB sertlik seviyesindeki çeliklerde, lazer kesim sonrasında çekme dayanımı ve akma dayanımında belirgin düşüşler raporlanmıştır. Bu çalışmada, ortalama 600 HB sertlikte zırh çeliğinde 1700 mm/dk kesim hızında gerçekleştirilen lazer kesim işleminin mekanik özellikler ve yüzey pürüzlülüğü üzerindeki etkileri deneysel olarak incelenmiştir. Kesim işlemleri sabit 1900 W lazer gücü, belirli odak konumu ve sabit gaz basıncı altında gerçekleştirilmiştir. Kesim sonrasında hazırlanan numunelerde akma dayanımı ($Rp_{0.2}$), çekme dayanımı (Rm) ve kopma uzaması (A%) değerleri ölçülmüş; ayrıca kesim yüzeylerinden pürüzlülük (Ra) değerleri elde edilmiştir. Elde edilen sonuçlar, lazer kesim sonrası çekme ve akma dayanımlarında belirgin bir düşüş gözlenmediğini, ancak kopma uzamasında(süneklik) ve yüzey pürüzlülüğünde ısıl etkiden kaynaklı değişimlerin meydana geldiğini göstermiştir. Bu bulgular, literatürdeki benzer çalışmalarda raporlanan yüksek düşüş değerlerinden farklı olarak, kullanılan kesim parametrelerinin ısı girdisini sınırladığı ve dolayısıyla mekanik özelliklerdeki değişimin minimum düzeyde kaldığını ortaya koymaktadır.

Anahtar Kelimeler: Zırh çeliği, Lazer kesim, Mikroyapı, Isı tesiri altındaki bölge (ITAB)

THE MECHANICAL EFFECTS OF LASER CUTTING ON ARMOR STEELS

ABSTRACT

The defense industry is one of the fastest-developing sectors today, and armored combat vehicles constitute a significant part of this field. Although materials such as aluminum, ceramics, and composites are also used in their production, steel remains the most commonly preferred material due to its formability, availability, and cost efficiency. Armor steels, which generally possess a martensitic microstructure with hardness levels around 600 HB, are typically shaped by laser cutting to achieve the geometries required by vehicle designs. However, the high thermal energy transferred to the material during laser cutting may cause microstructural transformations in these ultra-high-hardness steels, leading to changes in mechanical properties. In the literature, particularly for steels with hardness values near 600 HB, several studies have reported a considerable decrease in tensile and yield strength after laser cutting. In the present study, the effect of the laser cutting process at a constant cutting speed of 1700 mm/min on the mechanical properties and surface quality of armor steel with an average hardness of 600 HB was experimentally investigated. The cutting operations were carried out using a constant laser power of 1900 W, a fixed focal position, and constant assist-gas pressure. Following the cutting process, yield strength ($Rp_{0.2}$), ultimate tensile strength (Rm), and elongation at fracture (A%) values were measured on prepared specimens, while surface roughness (Ra) values were also obtained from the cut edges. The experimental results indicated no significant reduction in tensile and yield strengths after laser cutting, while a slight change in elongation and surface roughness was observed due to the localized thermal effects. These findings differ from the higher degradation levels reported in previous studies and suggest that the applied cutting parameters in this work effectively limited the thermal input, resulting in minimal variation in the mechanical behavior of the 600 HB armor steel.

Keywords: Armor steel, Laser cutting Microstructure, Heat affected zone (HAZ)

1. GİRİŞ

Günümüzde artan güvenlik tehditleri, askeri operasyonların çeşitlenmesi ve savunma sistemlerinin modernizasyonu, zırhlı muharebe araçlarının stratejik önemini giderek artırmaktadır. Bu araçlarda kullanılan malzemeler, yüksek mukavemet, düşük yoğunluk, darbe dayanımı ve maliyet etkinliği gibi kriterler doğrultusunda seçilmektedir. Zırh sistemlerinde kullanılan malzemeler arasında çelik, alüminyum, seramik ve kompozit esaslı malzemeler yer almakta; ancak şekillendirilebilirlik, kaynaklanabilirlik, üretim kolaylığı ve tedarik avantajı gibi nedenlerle zırh çelikleri en yaygın kullanılan malzeme türü olarak öne çıkmaktadır (Cimpoeru 2016). Zırh çeliklerinin üretim süreci, hedeflenen mekanik özelliklerin elde edilmesinde belirleyici rol oynamaktadır. Bu süreç genellikle yüksek alaşımlı çeliklerin dökümü ile başlamakta, ardından sıcak haddeleme işlemiyle devam etmektedir. Sıcak haddeleme, çeliğin yüksek sıcaklıklarda plastik deformasyona uğratılarak kalınlığının düşürülmesini ve homojen bir mikroyapı elde edilmesini sağlar. Elde edilen levhalar, daha sonra ısıl işlem basamaklarına tabi tutulur. Bu aşamada çelik, östenitleştirme sıcaklığına kadar ısıtılır, ardından su verme (quenching) işlemi ile hızla soğutularak martensitik yapı oluşturulur. Sonrasında uygulanan temperleme (tavlama) işlemi ise iç gerilmeleri azaltarak çeliğe tokluk kazandırır (ILSENBURGER Grobblech 2023). Bu işlem dizisi sonucunda, hem balistik dayanım hem de darbe tokluğu açısından yüksek performans gösteren, yaklaşık 600 HB sertlikte zırh çelikleri üretilmektedir.

Zırh çeliklerinin şekillendirilmesi ve montajında kullanılan işlemler arasında lazer kesim, plazma kesim, su jeti ve mekanik kesme yöntemleri yer almaktadır. Bu yöntemler arasında lazer kesim, sunduğu yüksek hassasiyet, dar kesim aralığı (kerf width), düşük deformasyon oranı ve seri üretim avantajları sayesinde tercih edilmektedir (Gao et al. 2020). Ancak lazer kesim işlemi sırasında malzeme yüzeyine aktarılan yüksek ısı girdisi, özellikle martensitik yapıya sahip yüksek sertlikteki çeliklerde mikroyapısal dönüşümlere neden olabilmektedir. Bu dönüşümler, kesim kenarına yakın bölgede temperlenmiş martensit, karbür çözünmesi veya ferritik dönüşüm şeklinde ortaya çıkar ve mekanik özelliklerde lokal değişimlere yol açabilir (Barényi et al. 2014). Lazer kesim parametreleri — özellikle kesim hızı, lazer gücü, odak konumu ve yardımcı gaz tipi — malzemenin ısı tesiri altındaki bölge (ITAB) genişliği ve yüzey kalitesi üzerinde doğrudan etkilidir (Nadkarni et al. 2021). Kesim hızı azaldığında, ışının malzeme üzerinde etki süresi artmakta ve ısı girdisi yükselmektedir; bu da ITAB genişlemesine ve mikroyapısal yumuşamaya yol açmaktadır. Tersine, kesim hızının artırılması, ısı girdisini sınırlayarak yapısal bozulmaların daha düşük seviyede kalmasını sağlar. Literatürde yapılan çalışmalar, düşük kesim hızlarında çekme ve akma dayanımlarında %10–20 arası azalma görülebileceğini, buna karşılık yüksek hızlarda yapılan kesimlerde bu etkinin minimuma indiğini göstermektedir (Khurshid et al. 2017; Gao et al. 2020). Zırh çelikleri üzerine yapılan çalışmalarda, özellikle 600 HB sertlik sınıfındaki malzemelerde, lazer kesim sonrası mekanik özelliklerde belirgin düşüşler raporlanmıştır (Barényi et al. 2014). Bunun temel nedeni, kesim sırasında açığa çıkan yüksek ısı enerjisinin yüzeye yakın bölgede martensitik dönüşümün kısmen tersine dönmesi ve lokal temperleme etkisi oluşturmasıdır. Ancak bazı araştırmalarda, kesim hızının artırılması veya uygun gaz kombinasyonlarının kullanılmasıyla bu etkinin sınırlanabildiği belirtilmiştir (Gao et al. 2020). Gerçekleştirilen bu çalışmada, yaklaşık 600 HB sertliğe sahip zırh çeliğinde farklı kesim hızlarında gerçekleştirilen lazer kesim işleminin mekanik özellikler (çekme ve akma dayanımı, kopma uzaması) ve yüzey pürüzlülüğü üzerindeki etkileri deneysel olarak incelenmiştir. Çalışmanın amacı, lazer kesim sırasında oluşan ısı girdisinin malzemenin mekanik bütünlüğünü ne ölçüde etkilediğini belirlemek ve literatürde bildirilen düşüş değerleriyle karşılaştırmalı bir değerlendirme sunmaktır.

2. MALZEME VE METOT

Deneysel çalışmada kullanılan zırh malzemesi kimyasal bileşim Tablo 1'de, mekanik özellikler ise Tablo 2'de verilmiştir.

Tablo 1. 600HB sertlikteki malzemeye ait kimyasal bileşim (% ağırlıkça)

Malzeme	C	Si	Mn	P	S	Cr	Ni	Mo	B
600HB	0,45	0,7	0,8	0,015	0,004	0,5	3,0	0,6	0,003

Tablo 2. 600HB sertlikteki malzemeye ait mekanik özellikler.

Malzeme	Akma Dayanımı (N/mm^2)	Çekme Dayanımı (N/mm^2)	Uzama (%)	Darbe Dayanımı (J)
600HB	1400	1950-2150	6	14 (-40°C)

8.5mm kalınlığındaki çekme numuneleri bystronic lazer kesim tezgahında kesilmiştir. Kesim parametreleri tablo 3'de verilmiştir.



Şekil 1. Bystronic lazer kesim tezgahı

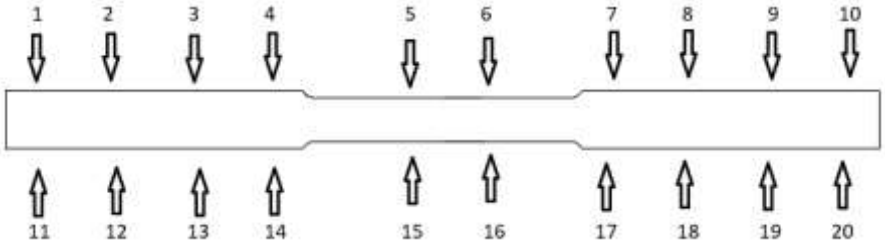
Tablo 3. 600HB sertlikteki malzemenin kesim parametreleri.

Malzeme	Lazer Gücü (W)	Kesme Hızı (mm/dk)	Gaz Basıncı (Bar)	Yardımcı Gaz
600HB	1900	1700	0.8	O_2

Kesilen numunelerin görüntüleri Şekil 2'de verilirken, yüzey pürüzlülük ölçümleri Tablo 5'de verilmiştir. Ölçümler, Mahr MarSurf PS1 pürüzlülük cihazı kullanılarak gerçekleştirilmiştir. Malzeme yüzeyinden 20 farklı noktadan ölçüm alınmış, alınan bölgeler Şekil 3'de gösterilmiştir. Elde edilen değerlerin ortalaması hesaplanmıştır. Ölçümler, DIN ISO 9013 standardı dikkate alınarak, malzeme kalınlığının 2/3 derinliğine kadar olan bölgeden gerçekleştirilmiştir.



Şekil 2. Kesilen Çekme Numuneleri



Şekil 3. Numune üzerindeki ölçüm noktaları

3. BULGULAR VE TARTIŞMA

Belirlenen kesim hızında hazırlanan numunelere ait çekme test sonuçları Tablo 4'de verilmiştir. Belirlenen hız için kesilen 3 numunenin akma mukavemeti ($Rp_{0.2}$), çekme dayanımı (Rm) ve kopma uzaması (A%) değerleri hesaplanmıştır.

Tablo 4. 600HB sertlikteki malzemeye ait çekme testi sonuçları.

Numune Adı	Akma Mukavemeti	Çekme Mukavemeti	Yüzde Uzama
	MPa	MPa	%
A	1557,34	2090,62	4,30
B	1575,70	2120,84	5,40
C	1570,10	2108,57	5,10

Elde edilen sonuçlar, tüm numunelerde çekme dayanımlarının 2090–2120 MPa aralığında akma dayanımnın ise 1500-1600 arasında kaldığını göstermektedir. Bu değerler, üretici firma verileriyle oldukça uyumludur.

Kesim hızının belirlenmesiyle birlikte kopma uzamasında belirgin bir azalma eğilimi gözlenmiştir; kesilen numunelerde yüzde uzama yüzde 5 civarına düşmüştür. Bu durum, lazer kesim sırasında seçilen parametrelerin ITAB genişliğinin daralması ve lokal gevrekleşme oluşmuş olacağını işaret etmektedir. Öte yandan, $Rp_{0.2}$ ve Rm değerlerinde istatistiksel olarak anlamlı bir değişim tespit edilmemiştir. Bu da lazer kesim sürecinin çeliğin optimal parametreler seçildiği takdirde mukavemetini önemli ölçüde değiştirmediğini göstermektedir.

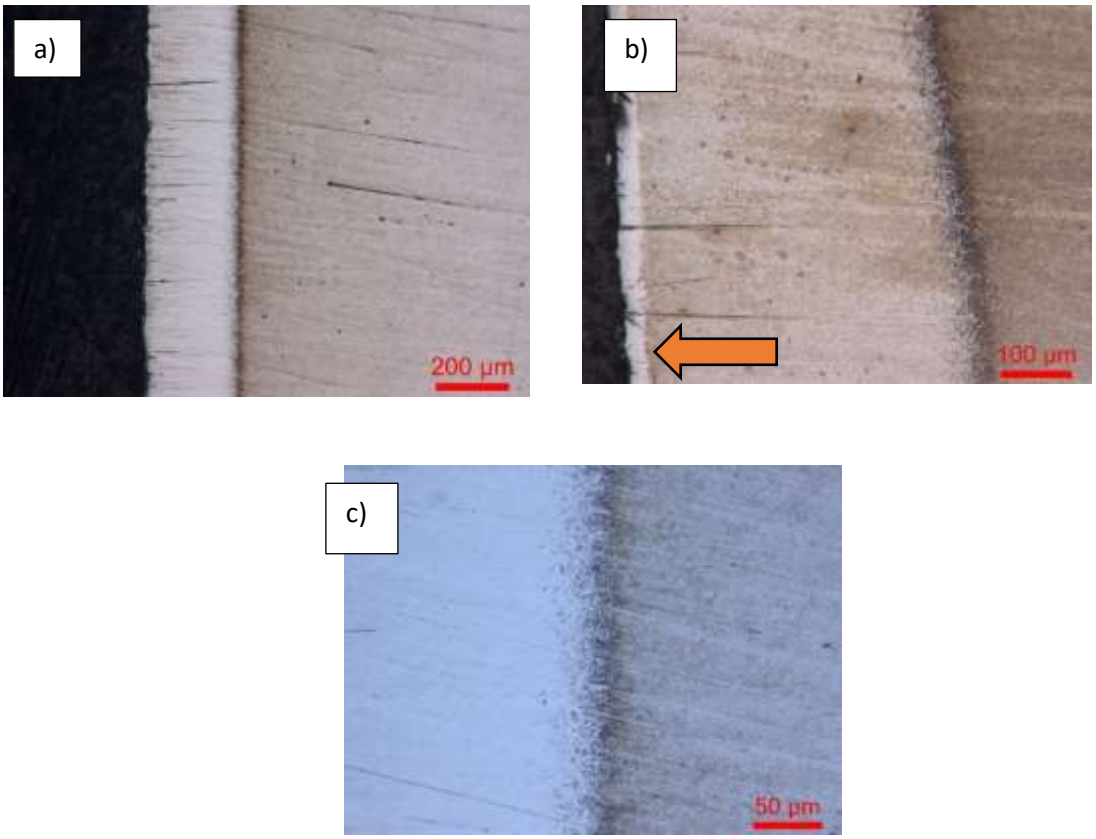
Kesilen ürünlerden alınan ölçümler Tablo 5'de verilmiştir.

Kesim yüzeylerinden alınan pürüzlülük ölçümleri, lazer kesimin yüzey kalitesini değerlendirmek amacıyla gerçekleştirilmiştir. Ölçümler DIN ISO 9013 standardına göre, malzeme kalınlığının 2/3 derinliğinden yapılmıştır.

Tablo 5. 600HB sertlikteki malzemeleye ait lazer kesim sonrası yüzey pürüzlülükleri

Sıra No	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	
A	2,797	3,303	2,598	2,646	2,525	2,947	2,803	2,847	2,809	2,805	
B	3,106	2,369	3,127	2,503	3,141	2,978	2,871	3,353	2,834	2,720	
C	2,362	3,001	2,656	3,160	3,229	3,088	2,916	2,749	2,823	2,828	
Sıra No	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**Ortalama**
A	3,353	2,852	2,808	2,825	2,835	2,771	2,821	3,303	3,229	2,777	**2,883**
B	2,785	3,206	2,819	2,822	3,229	2,773	2,784	2,873	2,828	2,810	**2,897**
C	2,700	2,854	2,802	2,745	2,821	2,825	2,826	2,759	2,795	2,832	**2,839**

Yüzey pürüzlülüğü değerleri, yüksek kesim hızının yüzey kalitesini iyileştirdiğini göstermektedir. Ra değerinin yaklaşık 2.8 µm seviyesinde olması, erime tabakasının minimum, yeniden katılaşma izlerinin sınırlı olduğunu göstermektedir. Bu bulgu, literatürde yüksek hızlarda ısı girdisinin azalmasıyla yüzey kalitesinin arttığını belirten çalışmalarla örtüşmektedir (Nadkarni et al. 2021).



Şekil 4. Kesilmiş zırh malzemesinin ITAB bölgesi mikroyapısı

(a)50x (b) 100x (c) 200x

Lazer kesim işlemi sonrasında elde edilen ve Şekil 4b'de verilen mikroyapı görüntüsü, ısı girdisinin malzeme üzerindeki etkisini net biçimde göstermektedir. Kesim yüzeyine en yakın bölgede, ergiyip katılaşma sonucu oluşan düzensiz, yönsüz ve mikroyapısal olarak homojen

olmayan bir tabaka gözlemlenmiştir. Literatürde bu bölge yeniden katılaşan tabaka (YKT) olarak tanımlanmakta olup, yüksek sıcaklık nedeniyle ergiyen malzemenin hızlı katılaşmasıyla oluştuğu belirtilmektedir (Saha et al., 2019). YKT tabakası, kesim işleminde en yüksek sıcaklıkla temas eden yüzeyidir.Şekil 4b'de okla gösterilmiştir. Yeniden katılaşan tabakanın hemen altında, kesim esnasında yüksek sıcaklıklara maruz kalmış ancak erimeye uğramamış bir bölge yer almaktadır. Bu bölge, yüksek sıcaklıkların etkisiyle martensitik yapının kısmen temperlenmiş martensite dönüştüğü ve iğnemsi morfolojide bozulmaların başladığı bir ısıdan etkilenmiş zon olarak değerlendirilmektedir. Nadkarni et al. (2021) bu bölgeyi, yüksek sıcaklıklı ısı tesiri altındaki bölge (YS-ITAB) olarak sınıflandırmakta ve özellikle temperlenme etkisiyle mikrosertlikte düşüş yaşanabileceğini belirtmektedir. YS-ITAB, lazer kesiminde oluşan en aktif dönüşüm zonlarından biridir. Bu yüksek sıcaklık etkisinin daha da az hissedildiği, kesim yüzeyinden uzaklaşan bölgelerde ise düşük sıcaklıklı ısı tesiri altındaki bölge (DS-ITAB) olarak adlandırılan, martensitik yapının büyük oranda korunduğu ancak ısının yine de mikro yapıda hafif düzenlenmelere neden olduğu bir zon tespit edilmiştir. Andrés et al. (2016), (DS-ITAB) bölgesinde iğnemsi martensitin daha net ayırt edilebildiğini ve mekanik özelliklerin bu bölgede büyük ölçüde korunduğunu ifade etmektedir. Bu zonlardan sonra gelen ana malzeme, herhangi bir ısı etkisine maruz kalmamış ve orijinal temperlenmiş martensitik yapısını koruyan alandır. Bu bölge, ısıl işlem sonrası kazanılmış olan nihai mekanik ve mikroyapısal özelliklerini muhafaza etmektedir. Bu morfolojik zon ayrımı, lazer kesim gibi yüksek enerji yoğunluklu işlemler sonrası oluşan termal etkileri anlamak açısından kritik önem taşımaktadır. Özellikle zırh çelikleri gibi sertleştirilmiş martensitik yapıya sahip malzemelerde bu geçişlerin net olarak analiz edilmesi, kesim parametrelerinin malzeme performansına olan etkilerinin değerlendirilmesine katkı sağlamaktadır.

4. SONUÇ

Bu çalışmada, yaklaşık 600 HB sertlik seviyesindeki zırh çeliğinin 1700 mm/dk kesim hızında lazerle kesilmesi sonrasında mekanik özelliklerinde ve yüzey kalitesinde meydana gelen değişimler kapsamlı biçimde değerlendirilmiştir. Çekme testi sonuçları, gerilme–şekil değiştirme davranışı ve yüzey pürüzlülüğü ölçümleri birlikte incelenerek lazer kesim sürecinin malzeme performansı üzerindeki etkisi ortaya konmuştur. 1700 mm/dk hızda kesilen numunelerde gerçekleştirilen çekme testleri, malzemenin akma dayanımı ($Rp_{0.2}$) ve çekme dayanımı (Rm) değerlerinde belirgin bir düşüş oluşmadığını göstermiştir. Ölçülen $Rp_{0.2}$ değeri yaklaşık 1600 MPa, Rm değeri ise 2130 MPa olarak bulunmuştur. Bu değerler, literatürde 600 HB sınıfı çelikler için verilen tipik dayanım aralıkları ($Rp_{0.2} \approx 1500–1700$ MPa, $Rm \approx 2000–2200$ MPa) ile tamamen uyumludur (Cimpoeru 2016). Bu sonuç, 1700 mm/dk kesim hızında lazerin malzeme üzerinde düşük bir ısı girdisi yaratması sayesinde, martensitik mikro yapının büyük ölçüde korunmuş olduğunu göstermektedir. Lazer kesim sonucunda oluşan ısı tesiri altındaki bölge (ITAB) dar kalmış, martensitten temperlenmiş martensite veya ferritik fazlara dönüşüm için gerekli süre sağlanmamıştır (Nadkarni et al., 2021; Saha et al., 2019; Andrés et al., 2016). Bu nedenle kesim sonrası mekanik bütünlüğün korunduğu söylenebilir. Yapılan mikroyapı analizleri, lazer kesim işleminin zırh çeliği üzerinde belirgin bir ısıdan etkilenmiş bölge (ITAB) oluşturduğunu göstermiştir. Kesim kenarına en yakın bölgede yeniden katılaşma tabakası (YKT), onun hemen altında ise sırasıyla yüksek ve düşük sıcaklık etkili ITAB bölgeleri tanımlanmıştır. Bu zonlar, mikroyapısal bozulma derecelerine göre ayrımlanmış ve temperlenmiş martensit yapıda kısmi dönüşümler gözlenmiştir. Ancak bu mikroyapısal değişimlere rağmen çekme testi sonuçlarında mekanik özelliklerde belirgin bir farklılık meydana gelmemiştir. Bu durum, doğru lazer parametreleri ile işlem yapıldığında lazer kesim yönteminin yüksek sertlikteki zırh çelikleri için uygulanabilir ve güvenilir olduğunu göstermektedir.

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YAKIT HÜCRESİ UYGULAMALARI İÇİN BİYOBOZUNUR RGO/P3HB4HB KOMPOZİT MEMBRANLARIN ÜRETİMİ VE KARAKTERİZASYONU

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ÖZET

Fosil temelli kaynakların hızla tükenmesi ve artan çevresel kaygılar, geleneksel polimerik malzemelere karşı biyolojik olarak parçalanabilir ve sürdürülebilir alternatiflerin araştırılmasını hızlandırmıştır. Bu çalışmada, biyolojik olarak parçalanabilir kopolimer poli(3-hidroksibutirat-ko-4-hidroksibutirat) (P3HB4HB) matris malzemesi ve indirgenmiş grafen oksit (rGO) iletken nano dolgu maddesi kullanılarak çevre dostu ve tamamen biyo-bazlı kompozit polimerik membranlar geliştirilmiştir. Çalışmada amaç, potansiyel yakıt hücresi uygulamaları için P3HB4HB membranlarının mekanik, termal ve proton iletkenlik özelliklerini iyileştirmektir. Farklı rGO yüklemeleri (ağırlıkça %0,5, 1, 3 ve 5) içeren kompozit membranlar, elektroçekim yöntemi ile üretildi. Termogravimetrik analiz (TGA), rGO ilavesiyle membranların termal stabilitesinin arttığını, rGO'nun termal olarak kararlı yapısı nedeniyle ise kalıntı kütlenin arttığını göstermiştir. Mekanik testler, %1 ağırlıkça rGO kompozitinin maksimum yük ve çekme dayanımında en yüksek uzama gösterdiğini ortaya koymuş ve bu bileşimde optimum dolgu maddesi dağılımını gözlenmiştir. Ancak, daha yüksek rGO içeriği esnekliğin azalmasına ve kırılganlığın artmasına neden olmuştur. Sıcaklığa bağlı proton iletkenliği ölçümleri, hidrojen bağı ağlarının oluşumu ve iyileştirilmiş yük transfer yolları sayesinde rGO'nun membran yapısı içindeki proton taşınımının arttığını göstermiştir. Genel olarak, orta miktarda rGO ilavesi, P3HB4HB membranlarının termal ve mekanik kararlılığını artırmıştır. Bu bulgular, rGO/ P3HB4HB kompozit membranların, mikrobiyal yakıt hücresi uygulamalarında sürdürülebilir ve çevre dostu proton değişim membranları için umut verici adaylar olduğunu göstermektedir.

Anahtar Kelimeler: Biyobozunur polimer; poli(3-hidroksibutirat-ko-4-hidroksibutirat) (P3HB4HB); İndirgenmiş grafen oksit (rGO); Mikrobiyal yakıt hücresi, Proton değişim membranı

PRODUCTION AND CHARACTERIZATION OF BIODEGRADABLE RGO/P3HB4HB COMPOSITE MEMBRANES FOR FUEL CELL APPLICATIONS

ABSTRACT

The rapid depletion of fossil-based resources and growing environmental concerns have accelerated the search for biodegradable and sustainable alternatives to traditional polymeric materials. In this study, environmentally friendly and fully bio-based polymeric composites membranes were developed using a biodegradable copolymer poly(3-hydroxybutyrate-co-4-hydroxybutyrate) (P3HB4HB) matrix material and reduced graphene oxide (rGO) conductive nano filler. The objective of study was to improve the mechanical, thermal and proton conductivity properties of P3HB4HB membranes for potential fuel cell applications. Composite membranes containing different rGO loadings (0.5, 1, 3 and 5 wt%) were produced using the electrospinning method. Thermogravimetric analysis (TGA) showed that the addition of rGO increased the thermal stability of the membranes, while the residual mass increased due to the thermally stable structure of rGO. Mechanical tests revealed that the 1% weight rGO composite exhibited the highest elongation at maximum load and tensile strength, indicating optimal distribution of the filler at this concentration. However, a higher rGO content has led to a decrease in flexibility and an increase in brittleness. Temperature-dependent proton conductivity measurements have shown that rGO enhances proton transport within the membrane structure due to the formation of hydrogen bond networks and improved charge transfer pathways. Generally, the addition of moderate amounts of rGO increased the thermal and mechanical stability of P3HB4HB membranes while maintaining their biodegradability. These findings indicate that rGO/P3HB4HB composite membranes are promising candidates for sustainable and environmentally friendly proton exchange membranes in microbial fuel cell applications.

Keywords: Biodegradable polymer; poly(3-hydroxybutyrate-co-4-hydroxybutyrate) (P3HB4HB); reduced graphene oxide (rGO); microbial fuel cell; proton exchange membrane

GİRİŞ

Küresel nüfusun ve teknolojik gelişimin hızlı artışı, geleneksel olarak fosil yakıtlarla karşılanan enerji talebinin artmasına neden olmuştur. Ancak, fosil kaynaklardan enerji üretimi, sera gazı emisyonları ve çevre kirliliği ile ilişkilidir. Ayrıca, fosil kaynakların sınırlı olması, petrol ihraç eden ülkelere bağımlılığı artırmaktadır (Martins, Felgueiras, and Smitková 2018). Sonuç olarak, yenilenebilir, sürdürülebilir ve karbon nötr enerji teknolojilerinin geliştirilmesi küresel bir öncelik haline gelmiştir (Ananthi et al. 2021). Maliyet etkin ve çevreye uyumlu yeşil teknolojilerin geliştirilmesi, kirliliği azaltırken gelecekteki enerji taleplerini karşılamak için gereklidir (M. Kumar et al. 2021). Bunlar arasında, mikrobiyal yakıt hücreleri (MYH'ler), organik bileşiklerin mikrobiyal oksidasyonu yoluyla aynı anda elektrik üretebilen ve atık suyu arıtabilen umut verici biyo-bazlı enerji sistemleri olarak ortaya çıkmıştır (Chauhan et al. 2022; Holder et al. 2016).

MYH'lerin temel bileşenlerinden biri, anot ve katot arasındaki proton transferini düzenleyen ve hücrenin genel verimliliğini doğrudan etkileyen proton değişim membranıdır (PEM). Ticari bir perflorosülfonik asit membran olan Nafion, yüksek maliyeti ve çevresel dezavantajlarına rağmen bu amaçla yaygın olarak kullanılmaktadır. Nafion, toplam sistem maliyetinin yaklaşık %38'ini oluşturduğu ve geri dönüştürülebilirlik sorunları yarattığı için, düşük maliyetli ve biyolojik olarak parçalanabilir membran alternatiflerinin geliştirilmesi büyük ilgi görmüştür (Ghasemi et al. 2013). Poli(eter eter keton) (PEEK), poli(eter sülfon) (PES), polisülfon (PSU), polibenzimidazol (PBI), poliimid (PI), poliamid (PA) ve polistiren (PS) gibi çeşitli sülfonlanmış sentetik polimerler alternatifler olarak incelenmiştir (Diaz, Abuin, and Corti 2012; Neves et al. 2010; Yang et al. 2009; Zhang and Shen 2012). Ancak, biyolojik olarak parçalanamayan yapıları uzun vadeli çevre sorunları yaratmakta ve sürdürülebilir MYH uygulamaları için biyo-bazlı ve çevre dostu membranlara olan ihtiyacı güçlendirmektedir. Petrol bazlı plastikler, dayanıklılıkları, korozyon dirençleri ve düşük ısı iletkenlikleri nedeniyle değerlidir, ancak ekosistemlerde kontrolsüz birikimlerinden dolayı "beyaz kirlilik" gibi ciddi çevre sorunlarına neden olmaktadır (Xanthos and Walker 2017; Frias and Nash 2019). Bu sorunu çözmek için biyolojik olarak parçalanabilir alternatiflerin geliştirilmesi zorunlu hale gelmiştir. Bunlar arasında, mikroorganizmalar tarafından hücre içi karbon ve enerji depolama malzemesi olarak sentezlenen çevre dostu ve biyouyumlu polimerler olan polihidroksialkanoatlar (PHA'lar) öne çıkmaktadır. PHA'lar hem karasal hem de deniz ortamlarında tamamen biyolojik olarak parçalanabilir ve CO_2 ve su gibi toksik olmayan yan ürünlere ayrışır (G. Q. Chen and Patel 2012; Sudesh, Abe, and Doi 2000; Park et al. 2024).

Bu çalışmada bir tür PHA kopolimeri olan poli(3-hidroksibutirat-ko-4-hidroksibutirat) (P3HB4HB), yakıt hücresi uygulamaları için potansiyel bir biyolojik olarak parçalanabilir membran malzemesi olarak seçilmiştir ve rGO destekli kompozit membranlar üretilmiştir. Grafen oksitin (GO) kısmi indirgenmesiyle elde edilen indirgenmiş grafen oksit (rGO), geniş bir yüzey alanına ve Grotthuss mekanizması yoluyla proton taşınmasını kolaylaştıran kalıntı oksijenli fonksiyonel gruplara sahiptir. (Karim et al. 2013; R. Kumar, Mamlouk, and Scott 2011; Pandey, Reifenberger, and Piner 2008). Bu bağlamda, mevcut çalışma, mikrobiyal yakıt hücrelerinde proton değişim membranı uygulamaları için uygunluklarını değerlendirmek üzere, rGO/P3HB4HB kompozit membranların geliştirilmesi ve karakterizasyonuna odaklanmaktadır.

MALZEMELER VE YÖNTEMLER

Malzemeler

P3HB4HB, PHABuilder (Shunyi County, China) firmasından TPTRPB3420-P34HB (10%) kodlu (Mw ≈ 700,000), 1,23 g/cm^3 yoğunluğa sahip, eriyik akış indeksi 2 gr/dk (180 °C, 2,16 kg) ve erime noktası 170 °C olan ürünü satın alınmıştır. Katkı maddesi olarak %99 saflıkta, 15,62 m^2/gr özgül yüzey alanına ve 4,5 µm boyuta sahip indirgenmiş grafen oksit (rGO) (Nanografi, Türkiye) takviye olarak kullanılmıştır. N, N-dimetilformamid (DMF), Kloroform (CF) (Sigma- Aldrich), satın alınmıştır.

Elektroçekim ile rGO/P3HB4HB Nanolif Membranların Hazırlanması

Deneysel çalışmalara başlamadan önce P3HB4HB polimeri, nem içeriğinin giderilmesi amacıyla vakumlu etüvde 80 °C'de 6 saat boyunca kurutulmuştur. Daha sonra, ağırlıkça %10 derişiminde P3HB4HB çözeltisi, 95/5 (v/v) oranındaki kloroform/DMF karışımında hazırlanarak manyetik karıştırıcıda 750 rpm hızında 18 saat karıştırılmıştır. Karıştırma işlemi tamamlandıktan sonra bekletilmeden elektroçekim işlemine geçilmiş; bu işlem 3 mL/saat besleme hızı, 15 cm iğne-toplayıcı mesafesi ve 10 kV uygulanan voltaj koşullarında gerçekleştirilmiştir. Elde edilen nanolif membranlar, test aşamasına kadar oda sıcaklığında desikatör içerisinde muhafaza edilmiştir. Nanoliflerin ortalama kalınlığı 130 ± 5 µm olarak belirlenmiştir. Üretilen membranlar, içerdiği rGO oranı esas alınarak adlandırılmıştır (örneğin, 1 rGO numunesi %1 rGO içeren nanolifi ifade etmektedir).

Karakterizasyon

Kompozit membranların mekanik özelliklerinin belirlenmesi amacı ile çekme testi Instron marka Universal Tester cihazı kullanılarak 10 mm/dk çekme hızında ASTM D882 standardına göre gerçekleştirilmiştir. Her bir bileşimden en az 5 numune oda sıcaklığında test edilmiştir. Test sonucunda elde edilen gerilme-gerinim grafiklerinden çekme dayanımı ve kopma uzaması değerleri elde edilmiş olup bu değerlerin ortalamaları raporlanmıştır.

Kompozit membranların termal bozunma ve ayrışma sıcaklıklarını analiz etmek için termogravimetrik analiz (TGA) kullanılmıştır. Ölçümler için Mettler Toledo TGA 1 cihazı kullanılmıştır. TGA, azot atmosferinde 10 °C/dk ısıtma hızında 25-600°C aralığında gerçekleştirilmiştir.

Proton iletkenlik ölçümleri, Gamry Reference 3000 Potansiyostat/Galvanostat kullanılarak, dört noktalı prob empedans spektroskopisi yöntemi ile gerçekleştirilmiştir. Düzlem içi proton iletkenliği ölçümleri için, membran örneği ile iki plaka elektrot, membranın bir yüzeyine yerleştirilen iki paralel platin elektrot aracılığıyla bir Teflon hücreye monte edilmiştir. Membran, platin elektrotlar arasında sıkıştırılmış ve hücre, %100 bağıl nemi korumak amacıyla deiyonize su ile doldurulmuş sıcaklık kontrollü bir ortamda konumlandırılmıştır. İletkenlik ölçümleri, 30 °C - 80 °C sıcaklık aralığında gerçekleştirilmiştir. Empedans ölçümleri sırasında 100 kHz–1 Hz frekans aralığında 10 mV AC sinyal genliği uygulanmıştır. Membran direnci (R), empedans eğrisinin yüksek frekans bölgesinin gerçek eksenle kesişim noktası kullanılarak belirlenmiştir.

Membranların su alım kapasitesi, deiyonize suya daldırılmadan önce ve sonra ölçülen ağırlık değişimleri esas alınarak belirlenmiştir. Kurutulmuş membranlar hassas terazi ile tartıldıktan sonra, 24 saat deiyonize suya daldırılmış, yüzeydeki fazla su filtre kağıdı ile giderildikten sonra son ağırlıkları ölçülmüş ve su alımı hesaplanmıştır.

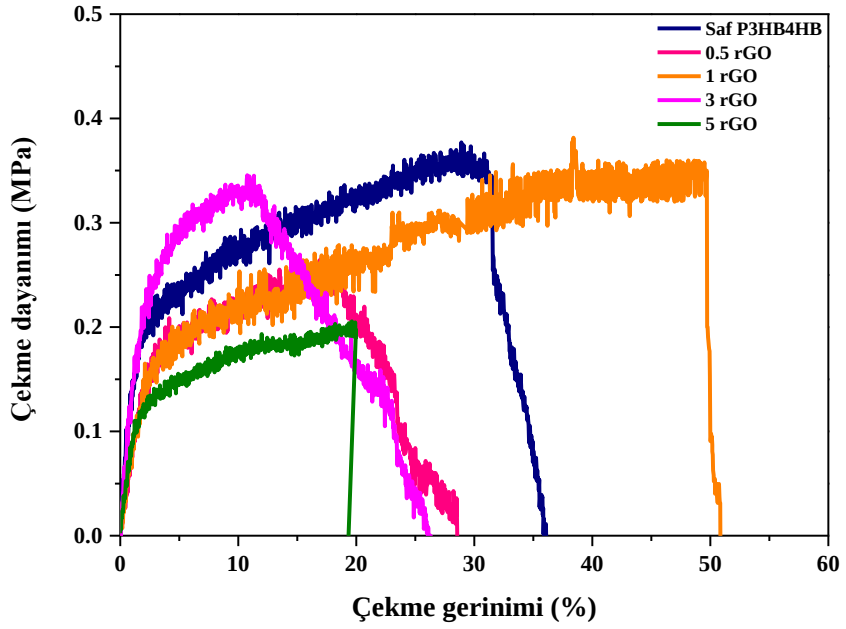
Membranların iyon değişim kapasitesi (IEC), asit-baz titrasyonu yöntemi kullanılarak belirlenmiştir. Kurutulmuş membranlar tartıldıktan sonra, H^+ iyonlarının çözeltideki Na^+

iyonları ile yer değiştirmesi için oda sıcaklığında 24 saat boyunca 1 M NaCl çözeltisine daldırılmıştır. Ardından, membrandan salınan H^+ iyonlarını tespit etmek amacıyla, asidik pH indikatörü fenolftalein kullanılarak 0,01 M NaOH çözeltisi ile titrasyon yapılmıştır. Membrandan salınan H^+ iyonlarının miktarı, IEC değerine dönüştürülmüştür.

BULGULAR VE TARTIŞMA

Mekanik Özellikler

P3HB4HB ve rGO bazlı kompozit nanolif membranlarının gerilme davranışı Şekil 1 ve Tablo 1'de gösterilmektedir. Saf P3HB4HB, maksimum yükte yaklaşık %36,8 uzama ile en yüksek gerilme dayanımı (0,37 MPa) sergilemiş ve sünek bir yapıya sahip olduğunu göstermiştir. Ağırlıkça %0,5 rGO ilavesi, gerilme mukavemetinin 0,25 MPa'ya düşmesine ve uzamanın %28,7'ye azalmasına neden olmuştur, bu da az miktarda rGO'nun polimer zinciri hareketliliğini hafifçe kısıtladığını göstermektedir. Bununla birlikte, %1 ağırlıkça rGO ilavesi uzamanın önemli ölçüde artmasına (%50,1) yol açarak, rGO nano tabakalarının homojen dağılımı sayesinde esneklik ve tokluğun arttığını gösterdi; bu da dolgu maddesi ile polimer matrisi arasındaki gerilim transferinin iyileştirmiştir. rGO içeriği ağırlıkça %3 ve %5 oranına arttıkça hem çekme dayanımı hem de uzama değerleri tekrar azalmıştır (sırasıyla 0,33 MPa ve 0,18 MPa; %26,9 ve %18,7). Bu eğilim, daha yüksek konsantrasyonlarda rGO'nun aglemerasyonu ile açıklanabilir; bu durum, gerilme yoğunlaştırıcıları olarak hareket etmiş ve arayüzey bağlarını zayıflatmış olabilir. Genel olarak, orta düzeyde rGO ilavesi (yaklaşık ağırlıkça %1) P3HB4HB'nin mekanik performansını artırırken, aşırı yükleme kırılganlığa ve sünekliğin azalmasına neden olmuştur.



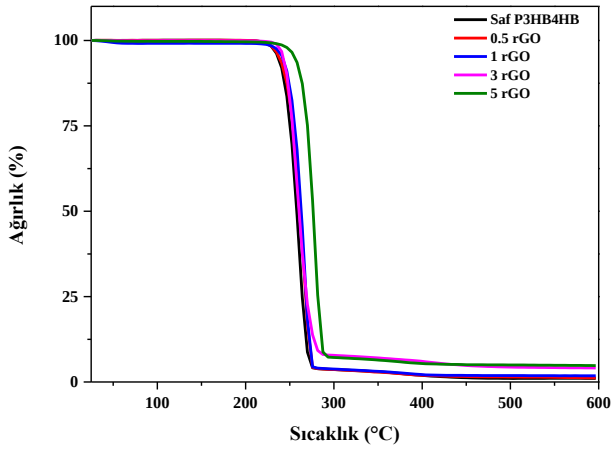
Şekil 1. Kompozit membranların çekme dayanımına karşı gerinim değerleri

Tablo 1. rGO/ P3HB4HB kompozit membranların mekanik özellikleri

Numune	Maksimum Yükte Çekme Dayanımı (MPa)	Young Modulu's (MPa)	Maksimum Yükte Uzama (%)
Saf P3HB4HB	0.37±0.05	17.9±0.76	36.8±2.61
0.5 rGO	0.25±0.01	11.1±1.10	28.7±2.37
1 rGO	0.37±0.05	13.4±0.67	**50.1**±6.97
3 rGO	0.33±0.03	12.1±1.30	26.9±0.29
5 rGO	0.18±0.01	10.3±0.87	18.7±0.11

Termogravimetrik özellikler

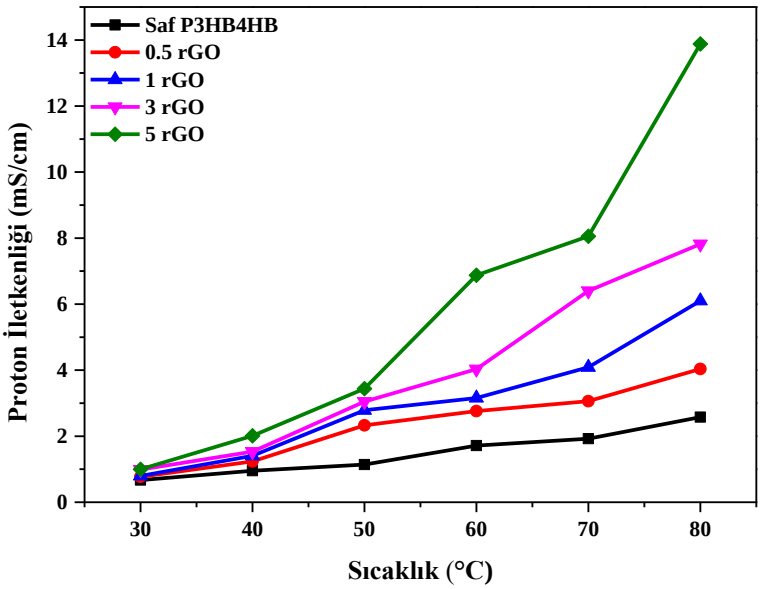
Saf P3HB4HB ve rGO/ P3HB4HB kompozit nanolif membranların ısıl bozunma davranışı TGA ile değerlendirilmiş ve ilgili termogramlar Şekil 2'de sunulmuştur. Saf P3HB4HB, maksimum bozunma sıcaklığı (T_{max}) 259,45 °C olan tek aşamalı ısıl bozunma sergilemiştir. rGO'nun eklenmesiyle, 0,5 rGO ve 1 rGO kompozitlerinde sırasıyla 264,90 °C ve 265,32 °C T_{max} değerleri ile ısıl karalılıkda hafif bir iyileşme gözlemlenmiştir. Bu iyileşme, polimer matris içindeki rGO tabakalarının iyi dağılımına atfedilebilir; bu da muhtemelen polimer zincirlerinin ısıl hareketini engellemiş ve ayrışmalarını geciktirmiştir. Bununla birlikte, 3 rGO numunesi, muhtemelen ısıl bariyer etkisini bozan rGO'nun bölgesel aglomerasyonu nedeniyle T_{max}'ta (259,03 °C) küçük bir düşüş gösterdi. İlginç bir şekilde, 5 rGO kompoziti en yüksek T_{max}'ı (277,90 °C) sergiledi, bu da daha yüksek miktarda rGO'nun, uygun şekilde dağıtıldığında daha güçlü arayüzey etkileşimlerini ve iyileştirilmiş ısı direncini teşvik edebileceğini düşündürmektedir. Ayrıca, 600 °C'de kalıntı miktarları değerlendirildiğinde, saf P3HB4HB için kalıntı değeri %1,05'ten 5 rGO kompozit için %4,79'a yükseldi, bu da rGO'nun yüksek ısıl karalılığını ve uçucu olmayan doğasını göstermektedir. Genel olarak, bu sonuçlar rGO'nun dahil edilmesinin, özellikle daha yüksek dolgu yüklemelerinde P3HB4HB'nin ısıl kararlılığını ve kalıntı içeriğini artırdığını göstermektedir.



Şekil 2. rGO destekli membranların TGA eğrileri

Proton İletkenliği

İletkenlik, tüm yakıt hücresi elektrolitleri için çok önemli bir faktördür ve proton iletkenliği, yakıt hücresi uygulamaları için membranları değerlendirmek için kullanılan temel özelliktir (Kim and Pivovar 2007). İyonların bir membrandan geçme yeteneği, iyonik veya proton iletkenliği olarak bilinir ve membranın protonları ne kadar etkili bir şekilde iletebileceğini belirler (Dharmalingam, Kugarajah, and Elumalai 2021). İçsel kütle iletkenliği ve membran kalınlığına bağlı olan hedef iletkenlik değeri, genellikle 0,05–0,1 S/cm aralığındadır. Çoğu proton ileten polimer için iletkenlik, membranın su içeriğine büyük ölçüde bağlıdır (de Bruijn et al. 2007). P3HB4HB'nin kendisi iyonik bir yapıya sahip olmasa da rGO'nun eklenmesinin iletkenlik yollarını geliştirerek proton taşınmasını kolaylaştırması beklenmektedir. Bununla birlikte, bu varsayımı doğrulamak için proton iletkenliğinin ölçülmüştür. Proton iletkenliği, yakıt hücrelerindeki proton değişim membranlarının performansında belirleyici bir rol oynadığından, membran seçiminde değerlendirilmesi kritik bir adımdır. Bu nedenle, bu çalışmada hazırlanan kompozit membranların sıcaklığa bağlı proton iletkenliği belirlenmiş ve Şekil 3'te sunulmuştur.



Şekil 3. Kompozit membranların proton iletkenlik değerleri

Genel olarak, tüm numunelerde sıcaklık artışıyla birlikte proton iletkenlik değerlerinin yükseldiği gözlenmiştir. Bu durum, sıcaklığın iyon hareketliliğini artırarak proton taşınımını hızlandırdığı yaygın olarak bilinen bir mekanizma ile açıklanabilir. Saf P3HB4HB membranı, test edilen sıcaklık aralığında en düşük proton iletkenliği sergilemiştir, bu da P3HB4HB'nin hidrofobik ve iletken olmayan doğası nedeniyle iyonik hareketi destekleme yeteneğinin sınırlı olmasının bir sonucudur. Ancak rGO katkısı ve katkı oranının artması ile proton iletkenliğinde belirgin bir iyileşme gözlemlenmiştir. Düşük katkı seviyelerinde (0,5 ve 1 rGO) iletkenlikte düşük artışlar sağlarken, 3 rGO ilavesinde bu eğilim daha belirgin hale gelmiştir. 5 rGO katkı içeren kompozit membranda iletkenlikte dikkate değer bir artış sağlanmıştır.

Su Alımı ve İyon Değişim Kapasitesi

Üretilen kompozit membranların su emme ve iyon değişim kapasitesi (IEC) değerleri Tablo 2'de özetlenmiştir. Proton değişim membranlarında proton taşınımı, protonların genellikle hidrojen bağına sahip su ağları veya iyon değişim grupları aracılığıyla hareket etmesinden dolayı su moleküllerine büyük ölçüde bağlıdır (X. Chen et al. 2010). Bu nedenle, proton iletkenliği su alımıyla artar, ancak aşırı şişme membran yapısını zayıflatabilir. P3HB4HB ve rGO gibi hidrofobik malzemelerin kullanılması bu sorunun önlenmesine yardımcı olur. Bu membranların nem içermediği, TGA analizinde 100 °C civarında nem kaybının olmaması ile doğrulanmıştır. İyon değişim kapasitesi (IEC), muhtemelen –COOH veya –SO_3H gibi güçlü asidik fonksiyonel grupların bulunmaması nedeniyle, rGO ilavesiyle önemli bir iyileşme göstermemiştir. rGO, iyon değişimi için daha az etkili olan –OH ve epoksi gruplarını içerir. Morfolojik gözlemler, saf P3HB4HB membranının ince, gözenekli nanofiberlere sahip olduğunu ve hidrofobik olmasına rağmen yüksek su emilimine yol açtığını göstermiştir. rGO ilavesiyle lifler daha kalın ve daha kompakt hale gelerek, özellikle %3 rGO'da gözenekliliği ve su emilimini azalttı. Ancak, daha yüksek rGO içeriklerinde (%5), lif yapısı tekrar daha düzenli ve gözenekli hale gelerek, biraz daha yüksek su emilimi sağladı. Bu sonuçlar, kontrollü rGO ilavesinin yapısal stabiliteyi iyileştirebileceğini ve proton taşınması için daha uygun bir morfoloji sağlayabileceğini göstermektedir.

Tablo 2. Kompozit membranların su emme ve iyon değişim kapasitesi

Membran	Membran Kalınlığı (cm)	Su Alımı (%)	IEC (meq/g)
Saf P3HB4HB	0,0130 ± 0,01	157	0,168
0.5 rGO	0,0130 ± 0,01	149	0,142
1 rGO	0,0130 ± 0,03	113	0,053
3 rGO	0,0130 ± 0,02	71	0,069
5 rGO	0,0130 ± 0,01	91	0,045

SONUÇLAR

Bu çalışma kapsamında, P3HB4HB membranlar, mekanik, termal ve proton iletkenlik özelliklerini iyileştirmek için çeşitli rGO yüklemeleriyle güçlendirildi. TGA sonuçları, rGO ilavesiyle membranların ısıl kararlılığını hafifçe arttığını, rGO'nun ısıl olarak kararlı yapısı nedeniyle ise kalıntı kütlesinin arttığını gösterdi. Mekanik analiz, %1 ağırlıkça rGO'nun gerilme dayanımı ve esneklik arasında en iyi dengeyi sağladığını, daha yüksek rGO içeriklerinin ise uzama oranının azalmasına ve kırılganlığın artmasına neden olduğunu ortaya koydu. Genel olarak, rGO'nun orta düzeyde eklenmesi, P3HB4HB membranların ısıl kararlılığını ve mekanik bütünlüğünü artırarak, yakıt hücresi uygulamalarında proton değişim membranı olarak kullanılabileceğini göstermiştir.

TEŞEKKÜRLER

Bu çalışma, Türkiye Bilimsel ve Teknolojik Araştırma Kurumu (TÜBİTAK) tarafından desteklenmiştir (Proje 124C192-TÜBİTAK 2218). Yazarlar, TÜBİTAK'a mali desteklerinden dolayı teşekkür eder.

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INVESTIGATION OF THE EFFECTS OF ZnO NANOPARTICLES ON THE STRUCTURAL, THERMAL AND MECHANICAL PROPERTIES OF PLA/PBS BASED COMPOSITES

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ABSTRACT

The growing demand for sustainable, high-performance materials has intensified research on bio-based polymer nanocomposites with multifunctional properties. This study reports the development of biodegradable nanocomposites by incorporating zinc oxide (ZnO) nanoparticles into a poly(lactic acid) (PLA)/poly(butylene succinate) (PBS) matrix. The blend, composed of 80% PLA and 20% PBS, provides renewability, biodegradability, and good processability, while ZnO nanoparticles (0–10 wt%) were introduced as functional fillers to enhance mechanical and thermal behavior. ZnO is a cost-effective, thermally stable, and environmentally benign metal oxide with semiconductive and photocatalytic properties. The composites were fabricated via melt extrusion followed by hot-press molding, suitable for scalable processing. Tensile testing revealed a significant decline in flexibility with increasing ZnO content: tensile strain dropped from 23% for the neat PLA/PBS blend to 5% with 1 wt% ZnO and below 1% at higher loadings, primarily due to filler aggregation. In contrast, tensile strength increased from ~15 MPa for the neat blend to ~45 MPa with 1 wt% ZnO, then decreased below 1 MPa at higher concentrations due to embrittlement. Thermogravimetric analysis (TGA) showed an ~80 °C reduction in onset degradation temperature with ZnO incorporation, while final mass correlated with filler content. Fourier-transform infrared spectroscopy (FTIR) revealed an intensified peak near 1600 cm^{-1} (O–H stretching) with increasing ZnO, without the appearance of new peaks. This work contributes to sustainable polymer development by elucidating the structural, thermal, and mechanical effects of ZnO nanoparticle incorporation in bio-based PLA/PBS composites.

Keywords: ZnO, PLA/PBS, melt mixing, mechanical properties

INTRODUCTION

The global production of petroleum-based plastics has surpassed 460 million tonnes annually, with inadequate end-of-life management leading to pervasive environmental pollution. Mismanaged plastic waste contributes approximately 1–2 million tonnes entering aquatic ecosystems each year, exacerbating biodiversity loss, microplastic infiltration into food chains, and greenhouse gas emissions throughout the plastic lifecycle [1, 2] . This escalating crisis has spurred extensive research into fully bio-based and biodegradable polymers that offer comparable or enhanced performance while facilitating circularity through industrial or home composting[3]. Poly(lactic acid) (PLA) stands as the most commercially viable bio-based polyester, sourced from renewable feedstocks like corn or sugarcane, and characterized by excellent transparency, high modulus, and scalable production[4]. Nonetheless, pristine PLA exhibits inherent brittleness (elongation at break typically <10%), low impact strength, sluggish crystallization kinetics, and a limited heat distortion temperature (~55–65 °C), which curtail its applicability in flexible or semi-durable products[5, 6]. Blending PLA with poly(butylene succinate) (PBS)—a ductile, biodegradable aliphatic polyester boasting elongation >300% and robust thermal stability—emerges as a premier strategy to enhance PLA's toughness while preserving renewability and compostability[7, 8]. PLA/PBS blends with 20–30 wt% PBS commonly display markedly improved ductility and processability, alongside satisfactory strength and complete biodegradability, positioning them as viable candidates for packaging, agricultural films, and biomedical devices [7]. To augment multifunctionality and performance, integrating nanofillers into biodegradable polymer blends represents a pivotal advancement for crafting next-generation sustainable materials endowed with attributes such as mechanical reinforcement, UV shielding, antimicrobial efficacy, and oxygen barrier capabilities[9]. Zinc oxide (ZnO) nanoparticles emerge as an exemplary nanofiller owing to their affordability, thermal resilience, GRAS (generally recognized as safe) designation, semiconducting nature, potent UV absorption, and substantiated antimicrobial/photocatalytic attributes, rendering them more eco-friendly than alternatives like silver or TiO_2 nanoparticles [10, 11]. Investigations into PLA/ZnO nanocomposites have underscored gains in tensile strength, modulus, and bioactive functionality at modest loadings (≤3 wt%), albeit with elevated concentrations prone to aggregation-driven embrittlement and hastened thermal degradation [11, 12]. Although progress in standalone PLA/ZnO and PLA/PBS systems is notable, the ternary PLA/PBS/ZnO configuration remains underexplored, especially concerning the delicate equilibrium of reinforcement, toughness preservation, filler dispersion, and thermal integrity across broad loading spectra (0–10 wt%). This study bridges this void by engineering melt-processable PLA/PBS (80/20) nanocomposites incorporating 0–10 wt% ZnO nanoparticles, and rigorously dissecting the attendant morphological, mechanical, and thermal trade-offs, thereby advancing the deliberate engineering of high-performance, wholly biodegradable, multifunctional materials for sustainable packaging and allied domains.

MATERIALS AND METHODS

Materials

PLA was acquired from NatureWorks under the trade name Ingeo2003D, with a density of 1.24 g/cm^3 and a melting point of 155 °C. PBS was procured from PTT MCC Biochem Co., Ltd. under the trade name BioPBS™ FZ71 PM, with a density of 1.26 g/cm^3 and a melting point of 115 °C.

Sample preparation

Firstly, the materials were dried in a vacuum oven at 80 ºC to remove the moisture. A laboratory-scale twin-screw Xplore brand mini-blender (extruder) was employed for blending. The extrusion was performed at 180 °C, 100 rpm, and 3 min. At the end of the melting process, the molten blend was transferred to the injection molding machine (Explore MI-12). The composites were molded at 8 bar with melt and mold temperatures of 180 °C and 25 °C, respectively.

Characterization

Structural properties were determined with Fourier transform infrared spectroscopy (FTIR) by using Perkin Elmer Spectrum 100. Measurements were performed at the range of 650-4000 cm^{-1} wavelength.

The mechanical properties of samples were determined by tensile test. The tests were performed using dog-bone specimens at a tensile speed of 5 mm/min according to ISO 527 5 A standard.

Thermogravimetric Analysis (TGA) was used to analyze the thermal strength and decomposition temperatures of the samples. Mettler Toledo TGA 1 device was employed for measurement and the analysis was carried out in the range of 25-600 °C with a heating rate of 10 °C/min.

RESULTS AND DISCUSSION

Fourier-transform infrared (FTIR)

Figure 1 presents the Fourier-transform infrared (FTIR) spectra of the neat PLA/PBS (80/20) blend and its nanocomposites containing 1, 3, 5, and 10 wt% ZnO nanoparticles in the wavenumber range of 3500–600 cm^{-1}. All spectra exhibit the characteristic absorption bands of the PLA/PBS matrix, including the strong C=O stretching vibration at 1748 cm^{-1}, symmetric and asymmetric C–O–C stretching at 1180, 1082, and 1042 cm^{-1}, and $–CH_3$ asymmetric and symmetric deformation at 1452 and 1386 cm^{-1}, and –CH stretching at 2960 cm^{-1}, with no significant shifts in peak position observed upon ZnO incorporation. No new absorption peaks appeared across the entire ZnO loading range (0–10 wt%), confirming the absence of chemical reactions or formation of new covalent bonds between the ZnO nanoparticles and the polymer chains during melt processing. The most prominent change is a progressive intensification and slight broadening of the broad band centered near 1600 cm^{-1}, which is assigned to O–H stretching vibrations of adsorbed water molecules and hydroxyl groups present on the ZnO nanoparticle surface. The intensity of this band increases systematically with ZnO content, being barely detectable in the neat PLA/PBS blend and becoming markedly pronounced at 10 wt% loading, reflecting the increasing availability of surface oxygen and hydroxyl groups contributed by the hydrophilic ZnO filler. A concomitant weak enhancement of the broad O–H band in the 3500–3200 cm^{-1} region further supports the incorporation of moisture-attracting ZnO surfaces within the composite. These observations indicate that the interaction between ZnO nanoparticles and the PLA/PBS matrix is predominantly physical in nature, with no evidence of chemical functionalization or grafting, while the increased hydroxyl-related absorbance highlights the growing contribution of the inorganic filler’s surface chemistry to the overall spectral profile of the nanocomposites.

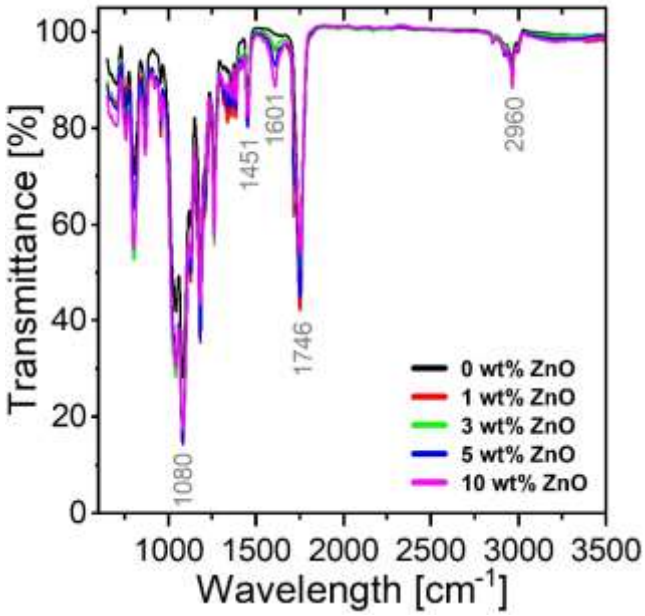

Figure 1. FTIR spectra of the neat PLA/PBS (80/20) blend and PLA/PBS/ZnO nanocomposites containing 1, 3, 5, and 10 wt% ZnO nanoparticles.

Thermogravimetric Analysis (TGA)

Figure 2 presents the thermogravimetric analysis (TGA) curves of the neat PLA/PBS (80/20) blend and PLA/PBS/ZnO nanocomposites containing 1, 3, 5, and 10 wt% ZnO nanoparticles, recorded under nitrogen atmosphere from 30 to 600 °C at a heating rate of 10 °C min^{-1}. The neat blend exhibits a single-step degradation profile with an onset temperature (defined as 5 % mass loss, T_5%) of approximately 300 °C and complete decomposition by ~400 °C, leaving virtually no residue (< 1%) at 600 °C. In contrast, incorporation of ZnO nanoparticles dramatically reduces thermal stability: the onset of degradation shifts to ~225–235 °C (a decrease of nearly 80 °C even at the lowest loading of 1 wt%), and the degradation proceeds through a distinct two-step process. The first major mass-loss step, occurring between ~220 and ~310 °C, accounts for approximately 70–80 wt% of the total mass and corresponds closely to the nominal PLA fraction in the blend matrix, indicating that ZnO selectively accelerates the thermal decomposition of the PLA phase, most likely via catalytic action of Zn^{2+} Lewis acid sites [13]. The second, smaller step between ~310 and ~400 °C corresponds to decomposition of the PBS-rich phase and follows a profile similar to that of the neat blend. Above 500 °C, the remaining mass plateau increases systematically with ZnO content, yielding final residues at 600 °C of approximately 3, 4, 6, and 11 wt% for the 1, 3, 5, and 10 wt% ZnO composites, respectively—values that align closely with the targeted filler loadings and thereby confirm successful incorporation of the inorganic nanoparticles throughout the series. These results underscore the strong catalytic influence of ZnO on the thermal degradation pathway of the PLA/PBS matrix, particularly its pronounced destabilizing effect on the PLA component.

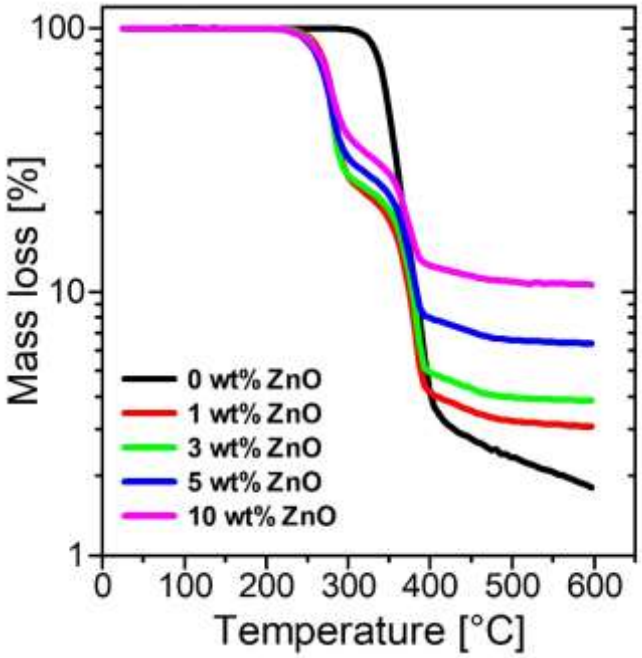

Figure 2: Thermogravimetric analysis curves of the neat PLA/PBS (80/20) blend and PLA/PBS/ZnO nanocomposites containing 1, 3, 5, and 10 wt% ZnO nanoparticles.

Tensile test

Figure 3 illustrates the tensile mechanical properties of the neat PLA/PBS (80/20) blend and its ZnO-loaded nanocomposites, with elongation at break presented in Figure 3a and the corresponding tensile strength (stress at break) summarized in Figure 3b (error bars represent the standard error of the mean calculated from five independent specimens per formulation). The unfilled PLA/PBS blend exhibits a ductile response typical of well-compatibilized systems, yielding a tensile strength of ~ 15 MPa and a remarkably high elongation at break of ~ 23 %, reflecting the effective toughening contribution of the 20 wt% PBS phase. Incorporation of only 1 wt% ZnO produces a pronounced reinforcing effect: tensile strength increases sharply to a maximum of ~ 44.8 Mpa at 1 wt% ZnO (an almost threefold improvement), while elongation at break simultaneously drops to ~ 5 %. This simultaneous gain in strength and loss of ductility indicates that low ZnO loadings act as efficient stress-transfer nanofillers that restrict chain mobility and promote stiffening of the matrix. At higher ZnO concentrations (≥3 wt%), however, both properties deteriorate catastrophically: tensile strength falls progressively to below 1 Mpa, while elongation at break collapses to <1 % across the entire high-loading regime. The drastic embrittlement and strength loss are directly attributable to severe nanoparticle aggregation, which creates stress-concentrating defect clusters, promotes premature crack initiation, and transforms the material from tough and deformable to extremely brittle. These results highlight a narrow processing window—centered around 1 wt% ZnO—where significant reinforcement can be achieved without complete sacrifice of ductility, whereas excessive filler content induces percolation of agglomerates and renders the nanocomposites mechanically unsuitable for most practical applications.

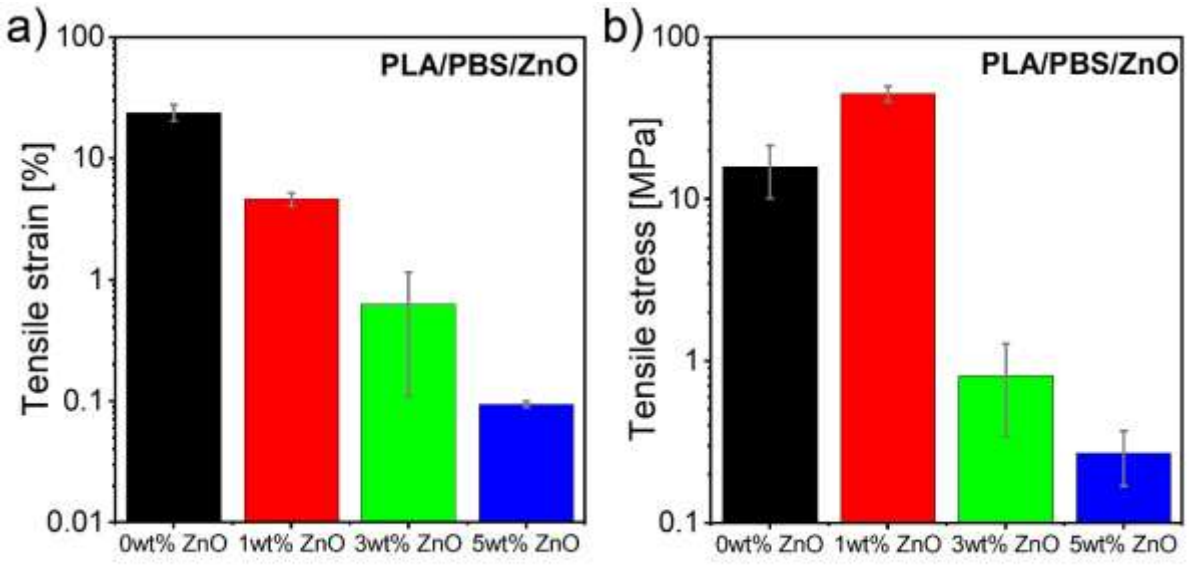

Figure 3: Tensile strain and tensile stress at break point of the neat PLA/PBS (80/20) blend and PLA/PBS/ZnO nanocomposites containing 1, 3, and 5 wt% ZnO nanoparticles.

CONCLUSION

Fully biodegradable PLA/PBS (80/20)/ZnO nanocomposites (0–10 wt%) were successfully prepared by melt extrusion and hot pressing. FTIR confirmed physical interactions only, with increasing O–H intensity due to ZnO surface hydroxyls and no new chemical bonds. TGA revealed a dramatic ~80 °C drop in onset degradation temperature and a shift to two-step decomposition, driven by selective catalytic acceleration of PLA degradation via Zn^{2+} Lewis acid sites, while residual mass accurately reflected ZnO content. Mechanical properties showed strong loading dependence: 1 wt% ZnO tripled tensile strength (~15 to ~45 MPa) but reduced elongation from 23 % to ~5 %. Higher loadings (≥3 wt%) caused severe aggregation, leading to extreme brittleness (elongation <1 %) and near-complete loss of strength (<1 MPa). Although low ZnO loadings offer significant reinforcement and potential multifunctionality, the accompanying loss of ductility and thermal stability limits practical utility. Future work should focus on improvement of dispersion through surface modification of fillers or use of compatibilizers to improve dispersion, thereby enabling the design of high-performance, multifunctional, biodegradable nanocomposites.

ACKNOWLEDGEMENT

The authors thank the Scientific Research Projects Unit of Kocaeli University (KOUBAP) for financial support under Project number FAA-2025-4580.

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BITKISEL BIYOSISTEMLERDE ELEKTROMANYETIK VE MANYETIK ALANLARIN ÇIMLENME VE STRES FIZYOLOJISINE ETKILERI

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ÖZET

Geleneksel yöntemlerle yapılan tarımsal üretim modellerinde birim alandan maksimum verim elde etmek amacıyla kimyasal girdilerin aşırı ve yoğun bir şekilde kullanılması çevresel sürdürülebilirliği olumsuz etkilemekte ve insan sağlığı açısından riskler doğurmaktadır. Bu nedenle, düşük maliyetli, çevre dostu ve uygulanması kolay fiziksel biyostimülasyon tekniklerine yönelik ilgi son yıllarda hızla artmıştır. Statik ve alternatif manyetik alanlar, elektromanyetik alanlar (EMF), manyetize su, soğuk plazma ve nanoteknoloji destekli magnetopriming uygulamaları; tohum çimlenmesi, fide gelişimi, fotosentetik kapasite, mineral alımı ve abiyotik stres dayanımı üzerinde olumlu etkiler gösterebilen yenilikçi yaklaşımlardır. Bu çalışmada, 2020–2025 yılları arasında yayımlanan güncel araştırmalar temel alınarak farklı manyetik/EMF uygulamalarının tohum fizyolojisi, erken büyüme performansı, fotosentez, biyokimyasal düzenlemeler ve moleküler yanıtlar üzerindeki etkileri değerlendirilmiştir. Yapılan araştırmalarda, manyetik/EMF uygulamalarının; doza, frekansa, maruz kalma süresine, manyetik akı yoğunluğuna, tohum türüne ve çevresel koşullara yüksek derecede duyarlı olduğu belirtilmiştir. Çoğu çalışma, EMF'nin uyarıcı- inhibitör olarak iki fazlı bir doz–tepki dinamiği sergilediğini vurgulamaktadır. Çalışmaların birçoğunda manyetik/EMF uyarımı; su alımı ve imbibisyon hızını artırmış, amilaz aktivitesine ve protein sentezine katkıda bulunmuş, metabolik süreçleri hızlandırmak suretiyle çimlenme oranını ve fide vigorunu yükselttiği bildirilmiştir. Bu çalışmalarda manyetik/EMF uygulamasının fotosentetik pigmentler ve klorofil içeriği üzerinde iyileştirici etkilere yol açtığı, ışık kullanım etkinliğini ve karbon asimilasyonunu artırdığı beyan edilmiştir. Ayrıca; manyetik/EMF uygulamalarının besin elementi alımını optimize ettiği, kök gelişimini güçlendirdiği ve nanoparçacık taşınımının kolaylaşmasına yardımcı olduğu belirtilmiştir. Araştırmada manyetik/EMF uygulamalarının biyokimyasal düzeyde etkilerinin incelendiği çalışmalara da yer verilmiştir. Bu çalışmalarda manyetik/EMF uygulamalarının ROS–antioksidan dengesini optimum düzeye getirerek oksidatif stresin azaltılmasında etkili rol aldığı belirtilmiştir. Buna ilaveten; bazı araştırmalarda manyetik/EMF uygulamasının; ABA, GA ve IAA gibi fitohormonların sentez ve dağılımında değişimlere neden olduğu ve bu sayede bitkilerde kuraklığa karşı dayanaklılık, tuz ve ağır metal streslerine karşı tolerans geliştirdiği belirlenmiştir. Ancak konu ile ilgili çalışmalar bütün olarak ele alındığında bazılarının birbiri ile çelişkili sonuçlar beyan ettiği gözlenmiştir. Bu farklı yaklaşımlardan yola çıkılarak manyetik/EMF uygulamalarının bitkisel materyal üzerindeki etki mekanizmalarının tam anlamıyla çözülmediği sonucuna varılabilir. Bu çalışmada, EMF tabanlı biyostimülasyonun tarımsal kullanım potansiyeli, sınırlarını ve gelecekteki araştırma konuları kapsamlı biçimde tartışılmıştır.

Anahtar Kelimeler: Bitki fizyolojisi, çevresel adaptasyon, serbest radikal yönetimi, büyüme hızlandırma teknikleri, metabolik aktivasyon, tarımsal yenilikçi uygulamalar

EFFECTS OF ELECTROMAGNETIC AND MAGNETIC FIELDS ON GERMINATION AND STRESS PHYSIOLOGY IN PLANT BIOSYSTEMS

ABSTRACT

In traditional agricultural production models, the excessive and intensive use of chemical inputs to maximize yield per unit area can harm environmental sustainability and pose risks to human health. As a result, interest in low-cost, environmentally friendly, and easy-to-implement physical bio-stimulation techniques has grown rapidly in recent years. Innovative approaches such as static and alternating magnetic fields, electromagnetic fields (EMF), magnetized water, cold plasma, and nanotechnology-supported magnetopriming have shown potential to positively influence seed germination, seedling development, photosynthetic capacity, mineral uptake, and abiotic stress tolerance. This study, based on recent research published between 2020 and 2025, examines the effects of various magnetic/EMF applications on seed physiology, early growth, photosynthesis, biochemical regulation, and molecular responses. The studies highlight that magnetic/EMF effects depend heavily on dose, frequency, exposure duration, magnetic flux density, seed type, and environmental conditions. Most research indicates that EMF shows a two-phase dose–response relationship, acting as both a stimulant and an inhibitor. Many studies report that magnetic/EMF stimulation improves water uptake and imbibition rates, increases amylase activity and protein synthesis, and enhances germination and seedling vigor by speeding up metabolic processes. These studies also note positive effects on photosynthetic pigments and chlorophyll content, which improve light utilization efficiency and carbon fixation. Moreover, magnetic/EMF treatments help optimize nutrient absorption, strengthen root development, and facilitate nanoparticle transport. Some research has explored the biochemical impacts of magnetic/EMF applications, revealing their role in reducing oxidative stress by balancing ROS and antioxidants. Additionally, certain studies have observed that magnetic/EMF exposure influences the synthesis and distribution of phytohormones, such as ABA, GA, and IAA, thus improving drought resistance and tolerance to salt and heavy metal stress. However, a review of the overall body of research shows conflicting results in some cases. Due to these varied findings, the mechanisms through which magnetic/EMF applications affect plant material are not yet fully understood. This study offers a comprehensive discussion of the potential, limitations, and future research directions for EMF-based bio-stimulation in agriculture.

Keywords: Plant physiology, environmental adaptation, free radical management, growth acceleration techniques, metabolic activation, innovative agricultural applications

1. GİRİŞ

Bitkisel biyosistemler, moleküler etkileşimlerden hücresel metabolizmaya, hücre/doku/organ büyümesi ve gelişimi ile çevresel tepkilere kadar çeşitli ölçeklerde biyolojik süreçleri içeren karmaşık, çok hücreli organizmalar olarak tanımlanmaktadır (Yang et al., 2020). Bu sistemlerin tasarımı, bitki sistemlerinin yapısının grafiksel bir görünümünü sağlayan çizge teorisi, genleri fenotipik özelliklere bağlayan mekanik modeller ve genetik olarak değiştirilmiş veya de novo bitki sistemlerinin genetik stabilitesi ile evrimleşe bilirliğini tahmin etmeyi sağlayan evrimsel dinamik teorisi gibi çeşitli teorik yaklaşımları içermektedir (Yang et al., 2020). Bitkiler ve çevresindeki biyolojik sistemler, gezegenin ve sakinlerinin gelecekteki sağlığı için merkezi bir öneme sahiptir (Henkhaus et al., 2020). Bitki sistemleri biyolojisi, genlerin, proteinlerin ve metabolitlerin belirli koşullar altında bu plastisiteyi gerçekleştirmek için nasıl birlikte çalıştığını ortaya koyan karmaşık moleküler etkileşimleri bütünsel bir yaklaşımla incelemektedir (Gechev & Petrov, 2022).

Elektromanyetik alanlar, elektrik yüklü nesneler tarafından üretilen ve biyolojik sistemlerle etkileşime giren hem elektrik hem de manyetik bileşenleri içeren fiziksel alanlardır (Murugan et al., 2023). Manyetik alanlar ise, EMF'nin hareketli elektrik yükleri tarafından oluşturulan ve elektrik alanından ayrı olarak ele alınan bir bileşenidir (Murugan et al., 2023). Doğal ve antropojenik kaynaklı elektromanyetik alanlar çevrede yaygın olarak bulunur ve bitkiler de dahil olmak üzere tüm biyolojik organizmalarla etkileşime girer (Schmidtpott et al., 2022). Özellikle yeni teknolojilerin uygulanmasıyla antropojenik kaynaklardan gelen alternatif EMF'lerin kalitesi ve niceliği artmaktadır (Schmidtpott et al., 2022). Elektrik ve manyetik alanlar, biyolojik sistemlerle etkileşime girebilen ortak bir elektromanyetik modalitenin ayrı bileşenleridir (Murugan et al., 2023). Canlı organizmalar elektriksel olarak nötr olsalar da elektromanyetizma ve termodinamik yasalarına uyan yüklü iyonlar, polarize moleküller ve elektrik alanlar içerirler (Romanenko et al., 2017).

EMF'lerin bitki gelişimi üzerindeki potansiyel etkileri hem olumsuz hem de faydalı sonuçlar doğurabilmektedir (Ayesha et al., 2023). Mevcut araştırmalar, radyo frekanslı EMF radyasyonunun bitki büyüme ve gelişimini, gen ekspresyonunu ve çeşitli metabolik aktiviteleri etkileyebileceğini göstermiştir (Czerwiński et al., 2023). Örneğin, marul bitkilerinde RF-EMF maruziyeti, fotosentetik verimlilikte önemli ve sistemik bir azalmaya ve çiçeklenme zamanının hızlanmasına yol açmıştır (Tran et al., 2023). Diğer taraftan, EMF'lerin tohum çimlenmesini, bitki beslenmesini, hassas tarımı, su kullanım verimliliğini, kök hidrolik iletkenliğini, bitki suyu alımını, anti-oksidatif savunmayı, zararlı önlemeyi, stres sinyallemesini ve hormonal yolları iyileştirerek mahsul verimliliğini artırabileceğine dair belirtiler de bulunmaktadır (Ayesha et al., 2023). Statik manyetik alanlar bitki hücrelerinin yapısını, biyokimyasal aktivitesini ve gen ekspresyonunu düzenleyebilir (Saletnik et al., 2022). SMF'lerin bitkiler üzerinde, fotosentetik verimlilik ve canlılık birikim indeksleri üzerinde önemli etkileri olduğu rapor edilmiştir (Saletnik et al., 2022). Ayrıca, SMF'lerin bitki fonksiyonlarını, büyümesini düzenlediği ve çevresel streslere karşı toleransı artırdığı da belirtilmiştir (Radhakrishnan, 2019). Yönlü bir elektromanyetik alanın, turp ve şeker kamışı bitkilerinin erken büyüme aşamalarında filizlerin ortaya çıkışını, filiz uzamasını, kök çoğalmasını ve bitki büyüme hormonlarını teşvik ettiği gözlemlenmiştir (Jo et al., 2024).

Bu çalışmanın amacı, elektromanyetik alanların belirli frekans ve şiddetlerde bitkisel biyosistemler üzerindeki etkilerini deneysel olarak incelemektir. Kapsam dahilinde, bitki büyüme indeksleri (çimlenme indeksleri gibi), fizyolojik stres göstergeleri ve moleküler düzeydeki değişimler analiz edilecektir. Bu araştırma, EMF'lerin bitkiler üzerindeki etkileşim

mekanizmalarını daha iyi anlamayı ve potansiyel tarımsal uygulamalar için bilgi sağlamayı hedeflemektedir.

2. ELEKTROMANYETİK ALANLARIN TEMEL PRENSİPLERİ

Elektromanyetik alanlar, frekans, şiddet ve dalga boyu gibi temel özelliklerle karakterize edilir (Suzuki et al., 2024). Frekans, birim zamanda dalga döngüsü sayısını (örneğin Hertz cinsinden) ifade eder ve biyolojik etkileşimlerin belirlenmesinde kritik bir parametredir (Suzuki et al., 2024). Şiddet veya alan gücü, elektrik alanlar için V/m, manyetik alanlar için ise Tesla (T) veya Gauss (G) birimleriyle ölçülerek, alanın bitkisel biyosistemler üzerindeki potansiyel etkisinin doz-tepki ilişkilerini anlamak için önem taşır (Czerwiński et al., 2019). Dalga boyu ise, dalganın bir tam döngüsünü tamamlamak için katettiği mesafeyi belirtir ve frekans ile ters orantılıdır (Suzuki et al., 2024). Bu parametreler, EMF'nin bitki hücreleri ile etkileşim biçimini ve sonuçlarını doğrudan etkilemektedir (Ayesha et al., 2023).

EMF'ler, bitki hücreleri ile çeşitli mekanizmalar aracılığıyla etkileşime girer (Schmidtpott et al., 2022). Doğal ve antropojenik kaynaklı EMF'ler çevrede yaygın olarak bulunur ve bitkiler de dahil olmak üzere tüm biyolojik organizmalarla etkileşime girer (Schmidtpott et al., 2022). Yüksek frekanslı iyonize olmayan elektromanyetik alanlar, bitkilerde stres koşulları altında gözlemlenenlere benzer spesifik yanıtlar uyandırabilen gerçek bir çevresel uyaran oluşturur (Vian et al., 2016). Bu etkileşimler, bitki büyümesi, gelişimi, gen ekspresyonu ve çeşitli metabolik aktiviteler üzerinde hem olumlu hem de olumsuz sonuçlar doğurabilir (Czerwiński et al., 2023). Statik manyetik alanlar, bitki hücrelerinin yapısını, biyokimyasal aktivitesini ve gen ekspresyonunu düzenleyebilir (Saletnik et al., 2022). SMF'lerin hücre şekli ve hücre zarı yapısı üzerinde güçlü bir etki göstererek, geçirgenliklerini artırdığı ve çeşitli metabolik yol aktivitelerini etkilediği belirtilmiştir (Saletnik et al., 2022).

İyon taşınımı ve membran potansiyeli, EMF'nin bitki hücreleri üzerindeki biyofiziksel etkileşimlerinin merkezinde yer almaktadır (Bajagić et al., 2023). Canlı organizmalar elektriksel olarak nötr olsalar da elektromanyetizma ve termodinamik yasalarına uyan yüklü iyonlar, polarize moleküller ve elektrik alanlar içerirler (Romanenko et al., 2017). Darbeli elektromanyetik alanların etki mekanizmasının, bitki hücrelerindeki membran elektro potansiyeli ve protein ve enzim aktiviteleri gibi çeşitli biyokimyasal süreçleri etkilediği belirtilmiştir (Bajagić et al., 2023). Bu, yüklü parçacıkların hücre zarı boyunca hareketini etkileyerek su ve besin maddelerinin daha hızlı emilimini sağlayabilir, bu da bitkilerin daha hızlı büyümesine ve iklim koşullarına karşı daha dirençli olmasına katkıda bulunabilir (Bajagić et al., 2023). Aşırı yüksek frekanslı elektromanyetik alanlara maruz kalma, yapay bir akson modelinde transmembran potasyum akışını artırarak elektriksel sinyal yayılımını kolaylaştırmaktadır (D'Agostino et al., 2018). Ayrıca, elektrik sinyallerinin yayılımının, iyon kanallarının ve plazma zarındaki H+-ATPaz aktivitesinin faaliyetleri ile ilişkili olabileceği de düşünülmektedir (Sukhova & Sukhov, 2021).

EMF'nin biyofiziksel rolü, esasen fiziksel alanların biyolojik moleküller ve yapılarla doğrudan etkileşimine dayanır (Romanenko et al., 2017). Elektrik ve manyetik alanlar, biyolojik sistemlerle etkileşime girebilen ortak bir elektromanyetik modalitenin ayrı bileşenleridir (Murugan et al., 2023). EMF'ler, biyolojik sistemlerdeki yüklü iyonlar, polarize moleküller ve elektrik alanlar üzerinde kuvvet uygulayarak hücresel süreçleri etkileyebilir (Romanenko et al., 2017). Bu etkileşimler sonucunda, gen ekspresyonu, fitohormon sentezi, fotosentez, solunum, floem kütle akışı ve ATP içeriği gibi çok sayıda fizyolojik süreç etkilenebilir (Sukhova & Sukhov, 2021). Bu değişikliklerin, bitkilerin stres faktörlerine karşı toleransını artırdığı ve belirli moleküler yapıların hasarlarının uyarılmasıyla ilişkili olabileceği düşünülmektedir (Sukhova & Sukhov, 2021).

3. MANYETİK ALANLARIN BİYOFİZİKSEL ETKİLERİ

3.1 Statik Manyetik Alan Tanımı

Statik manyetik alanlar, biyolojik sistemler üzerindeki etkileri nedeniyle uzun yıllardır bilimsel ilgi odağı olmuştur (Saletnik et al., 2022). Dünya'nın manyetik alanı (jeomanyetik alan, GMF) tüm canlı organizmalar için kaçınılmaz bir çevresel faktör olup, yeryüzünde 25 ila 65 μT arasında değişen bir yoğunluğa sahiptir ve bir statik manyetik alan olarak kabul edilir (Bellino et al., 2023). Araştırmacılar, bitki türleri üzerindeki GMF etkilerini taklit etmek veya güçlendirmek amacıyla farklı parametrelerde SMF'ler kullanmaktadır (Zhou et al., 2024). Magnetopriming çalışmalarında, zayıf statik homojen manyetik alanlar (0–100 μT dahil GMF) ve güçlü homojen manyetik alanlar (milliTesla ila Tesla) gibi çeşitli manyetik alan türleri incelenmiştir (Sarraf et al., 2020).

3.2 Paramanyetik İyonlar Üzerindeki Etkiler

Manyetik alanlar, bitki hücrelerindeki iyon kanallarının geçirgenliğini etkileyerek maddelerin hücre içine taşınımını değiştirebilmektedir (Kornarzyński et al., 2020). Ayrıca hormon ve enzim konsantrasyonlarında değişikliklere yol açabilirler (Kornarzyński et al., 2020). Manyetik alanın etkisi altında, su moleküllerinin ve çözünmüş iyonların dış elektron kabukları polarize olarak iyon hidrasyon koşullarında değişimlere neden olabilir (Kornarzyński et al., 2020). Jeomanyetik alanın azaltılması (sıfıra yakın manyetik alan, NNMF) bitki dokularındaki metallerin, özellikle demir ve çinko birikimini etkilemektedir (Islam et al., 2020). SMF, bitkilerin demir homeostazisini sürdürmelerine yardımcı olmakta ve demir metabolizmasıyla ilgili genlerin aşağı regüle olmasına rağmen bitki dokularındaki demir içeriğinin nispeten değişmeden kalmasını sağlayabilir (Zhou et al., 2024). Radikal çift mekanizması, manyetik alanın redoks reaksiyon hızları üzerindeki etkileri ve dolayısıyla serbest radikaller ile reaktif oksijen türleri konsantrasyonlarındaki değişimlerle açıklanmaktadır (Parmagnani et al., 2022).

3.3 Su Yapısının Değişimi ve İmbibisyon Üzerindeki Etkiler

Manyetik alanlar, suyun yapısal özelliklerini ve bitkilerdeki imbibisyon süreçlerini önemli ölçüde etkilemektedir (Dobránszki, 2023). Bir manyetik alanın etkisi altında, su moleküllerinin ve çözünmüş iyonların dış elektron kabuklarının polarize olması, iyon hidrasyon koşullarında değişikliklere ve kristalleşme çekirdeklerinin oluşumuna yol açabilmektedir (Kornarzyński et al., 2020). Bitki materyalindeki su ile manyetik alan etkileşimi, suyun elektriksel iletkenliğinde bir artışa ve yüzey geriliminde bir azalmaya neden olabilir (Kornarzyński et al., 2020). Bu durum, sudaki yüklü parçacıklar (iyonlar) üzerindeki Lorentz kuvvetinin, dış manyetik alana karşılık gelen geçici polarizasyona yol açmasından kaynaklanmaktadır (Kornarzyński et al., 2020). Manyetize su, moleküllerini kompleksler halinde daha kolay bağlayabilir ve stres altındaki dokularda daha iyi tutabilir (Ergashova et al., 2023). Zayıf bir manyetik alana maruz bırakılan su, dielektrik sabitini değiştirebilir, bu da fiziksel özelliklerini etkileyebilir (Abu-Saied et al., 2023). Manyetik işlem, suyun fiziksel, kimyasal, biyofiziksel ve fiziko-kimyasal özelliklerini değiştirebilir; bu değişiklikler arasında hidrojen bağı oluşumu, iletkenlik, aktivasyon enerjisi, yüzey gerilimi, su moleküllerinin boyutu ve yapısal düzenlilik bulunmaktadır (Alattar et al., 2022).

3.4 Fotosentetik ve Metabolik Etkiler

Manyetik alanlar, bitkilerin fotosentetik verimliliği ve metabolik süreçleri üzerinde belirgin etkiler yaratmaktadır (Schmidtpott et al., 2022). Manyetik alanlar, biyokütle fotosentez verimliliği ve canlılık birikim indeksleri üzerinde önemli bir etkiye sahiptir (Saletnik et al., 2022). SMF uygulaması, reaktif oksijen türlerinin oluşumunu ve birikimini hızlandırsa da aynı zamanda antioksidan enzimlerin yüksek aktivitesine yol açarak oksidatif stresi azaltmaktadır

(Saletnik et al., 2022). SMF'ler, hücre şekli ve hücre zarı yapısı üzerinde güçlü bir etki göstererek geçirgenliklerini artırır ve çeşitli metabolik yolları etkileyebilir (Saletnik et al., 2022). SMF'ye maruz kalma, bitkilerin ROS seviyelerini düşürmesine ve antioksidan enzim aktivitesini ve nikotinamid birikimini artırarak oksidan dengesini sinerjik olarak sürdürmesine yardımcı olmaktadır (Zhou et al., 2024). Manyetik alan uyarımı, protein ve minerallerin gruplanmasını artırabilir veya fotosentezi iyileştirebilir (Kornarzyński et al., 2018). Karşılaştırmalı transkriptomik analizler, oksin sentezi ve sinyal iletimi genlerinin SMF maruziyetiyle yukarı regüle olduğunu göstermiştir (Zhou et al., 2024). Jeomanyetik alanın azaltılması, ROS temizleyici enzimlerin ve H_2O_2 üretiminin metabolomik ve transkriptomik modülasyonuna yol açar (Parmagnani et al., 2022). Yüksek jeomanyetik değişkenlik altında Elodea bitkilerinde günlük oksijen üretiminde azalma gözlemlenmesi, jeomanyetik bozulmanın fotosentez gibi metabolik süreçleri etkileyebileceğini düşündürmektedir (Thoradit et al., 2023). Transkriptom analizi, EMF maruziyeti sonrası transkript miktarlarında değişiklikler ve fotosentetik ile merkezi enerji metabolizmasındaki varyasyonlarla birlikte metabolit havuz boyutlarında yeniden düzenlemeler olduğunu ortaya koymuştur (Schmidtpott et al., 2022).

3.5.ÇİMLENME PARAMETRELERİNE ETKİLER

Elektromanyetik alanlar ve manyetik alanlar, bitki tohumlarının çimlenme süreçleri üzerinde çeşitli etkilere sahiptir. Bu etkiler, çimlenme indeksleri, enzimatik aktivite, tohum kabuğu geçirgenliği, fide gelişimi ve kök mimarisi gibi parametreler üzerinden incelenmektedir.

Çimlenme İndeksleri

Manyetik alan uyarımlarının tohum çimlenme hızı üzerinde belirgin etkileri gözlemlenmektedir (Dziwulska-Hunek et al., 2023). Tohumların manyetik alanlara maruz bırakılması, çimlenme yüzdesi, çimlenme hızı indeksi ve çimlenme hızı katsayısı gibi çimlenme parametrelerinde önemli artışlar sağlayabilmektedir (El-Sayed, 2023). Örneğin, soya fasulyesi tohumlarında statik manyetik alanın, daha hızlı çimlenme ve artan çimlenme oranı sağladığı bildirilmiştir (Bezerra et al., 2023). Bir çalışmada, belirli manyetik alan yoğunluklarının (0.1 mT) optimum çimlenme süresi, gövde büyümesi ve klorofil içeriği gibi parametrelerde en iyi sonuçları verdiği belirtilmiştir (Tirono, 2022). Manyetik olarak işlenmiş suyun kullanımı, çimlenme ve fide parametreleri, büyüme ve verim üzerinde faydalar sağlayabilmektedir (Selim et al., 2022).

3.6 EMF'nin Enzimatik Aktiviteye Etkisi

Manyetik alanların, tohumlarda meydana gelen biyokimyasal süreçlerdeki protein ve enzim aktivitelerini uyararak çimlenmeyi etkilediği literatürde yer almaktadır (Dziwulska-Hunek et al., 2023). Bitkilerde kriptokrom adı verilen mavi ışık reseptörleri, uyarıldığında radikal çiftleri oluşturarak proteinlerin radikal tabanlı manyetik sensörler olarak işlev görmesini sağlamaktadır (Dziwulska-Hunek et al., 2023). Bu mekanizma, manyetik alanların enzimatik süreçler üzerindeki etkisinin temelini oluşturabilir. Elektromanyetik alanlara maruz kalan ürün tohumlarında, fotosentez ve enzimatik kimyasal reaksiyonlarda önemli bir artış kaydedilmiş, bu da bitki büyümesini hızlandırmıştır (El-Sayed, 2023). Ayrıca, manyetik alan, iyon kanallarının geçirgenliğini etkileyerek hücrelere madde taşınımını değiştirebilir, hormon ve enzim konsantrasyonlarında değişikliklere yol açabilir (Kornarzyński et al., 2020).

3.7 Manyetik Alanın Kabuk Geçirgenliğini Artırması

Manyetik alanın etkisi altında, su moleküllerinin ve çözünmüş iyonların dış elektron kabukları polarize olabilir, bu da iyon hidrasyon koşullarında değişikliklere neden olabilir (Kornarzyński et al., 2020). Tohumların manyetik alanlara maruz bırakılmasıyla tohum kabuğunun geçirgenliğinin iyileştiği gözlemlenmiştir (Tomeková et al., 2023). Bu durum, suyun elektriksel iletkenliğinde bir artışa ve yüzey geriliminde bir azalmaya yol açarak tohumların su alımını

(imbibisyon) kolaylaştırabilir (Kornarzyński et al., 2020). Tohum kabuğunun sertliği ve suya geçirimsizliği gibi nedenlerle zayıf veya engelli çimlenme yaşayan tohumlarda, manyetik alan uygulamaları çimlenmeyi teşvik edebilir (Dziwulska-Hunek et al., 2023).

3.8 Fide Gelişimi ve Kök Mimarisi Üzerindeki Etkiler

Manyetik alanların fide gelişimi ve kök mimarisi üzerinde belirgin etkileri bulunmaktadır (Bernard, 2024). Statik manyetik alanların kök büyümesini teşvik ettiği ve Arabidopsis bitkilerinde kökün manyetik alan etkilerini doğrulamak için ideal bir sistem olabileceği belirtilmiştir (Zhou et al., 2024). Manyetize su kullanımı hem sert buğday hem de mercimek genotiplerinde kök uzamasını artırmıştır (Sestili et al., 2023). Manyetik alanların kök ucundaki iyon kanallarının geçirgenliğini etkileyerek, besin ve su alımını optimize edebileceği düşünülmektedir (Islam et al., 2020). GMF'nin kök ve sürgünlerdeki genleri düzenlediği, ancak genlerin %49'unun bu organlarda ters yönde düzenlendiği, yani yerleşik sinyal ağlarının spesifik genlerin yukarı veya aşağı regülasyonunu belirlediği belirtilmiştir (Paponov et al., 2021). Bu da manyetik alanların bitki gelişimindeki karmaşık rolünü vurgulamaktadır.

4. FİZYOLOJİK VE BİYOKİMYASAL STRES YANITLARI

4.1 Oksidatif Stres Göstergeleri (MDA, PRO, H_2O_2, ROS)

Elektromanyetik alanlara ve manyetik alanlara maruz kalmak, bitkilerde reaktif oksijen türleri metabolizması ve sitozolik kalsiyumda artışa yol açarak hücresel tepkileri tetikleyebilir (Kaur et al., 2021). Bu durum, gen ekspresyonu ve/veya enzimatik aktivitelerde değişikliklere yol açarak hücrelerde hemen veya gecikmeli olarak bitki büyüme değişiklikleri meydana getirebilir (Kaur et al., 2021). Düşük frekanslı elektromanyetik alanların, hücreler arası serbest radikal homeostazını değiştirdiği ve stres tepkileriyle ilgili genlerin ekspresyonunu etkilediği öne sürülmektedir (Kostyń et al., 2023). Özellikle radyo frekanslı maruziyet, ROS oluşumunu etkileyen iki önemli homeostatik sistem olan kalsiyum hareketini ve ROS oluşumunu etkilemektedir (Tran et al., 2023). Örneğin, 900 MHz radyasyona maruz kalan domates bitkilerinde calmodulin (calm-n6) ve kalsiyum bağımlı protein kinaz (lecdpk1) seviyelerinde artış gözlemlenmiştir (Tran et al., 2023). Ayrıca, 900 MHz radyasyona maruz kaldıktan sonra, mung fasulyesinde H_2O_2 birikiminde artış ve ROS temizleme enzim aktivitelerinde önemli bir yukarı regülasyon tespit edilmiştir (Tran et al., 2023).

Jeomanyetik alanın azaltılması (near-null magnetic field, NNMF), Arabidopsis thaliana'da ROS temizleyici enzimlerin metabolomik ve transkriptomik modülasyonuna ve H_2O_2 üretimine yol açmaktadır (Parmagnani et al., 2022). Statik manyetik alan uygulaması, reaktif oksijen türlerinin oluşumunu ve birikimini hızlandırsa da aynı zamanda antioksidan enzimlerin yüksek aktivitesine yol açarak oksidatif stresi azaltmaktadır (Saletnik et al., 2022). SMF'ye maruz kalma, bitkilerin ROS seviyesini düşürmesine ve antioksidan enzim aktivitesini ve nikotinamid birikimini artırarak oksidan dengesini sinerjik olarak sürdürmesine yardımcı olmaktadır (Zhou et al., 2024). Şuman rezonans aralığındaki manyetik alanların buğday ve bezelye bitkilerinin redoks metabolizması üzerindeki etkileri incelendiğinde, katalaz ve süperoksit dismutaz aktiviteleri ile malondialdehit içeriği gibi parametrelerde değişiklikler gözlemlenmiştir (Mshenskaya et al., 2022). MDA, lipid peroksidasyonunun bir ürünü olup, oksidatif stresin önemli bir göstergesidir. Başka bir çalışmada, statik manyetik alana maruz kalan marul fidelerinde hidrojen peroksit, süperoksit radikali ve lipid peroksidasyonu gibi oksidatif hasar kriterlerinin kontrol gruplarına göre düşük seviyelerde tutulduğu belirtilmiştir (Latef et al., 2020).

4.2 Antioksidan Enzim Aktiviteleri

Manyetik alanların bitkilerdeki antioksidan enzim aktiviteleri üzerinde düzenleyici etkileri bulunmaktadır (Saletnik et al., 2022). Statik manyetik alanlar reaktif oksijen türlerinin oluşumunu ve birikimini artırırken, aynı zamanda antioksidan enzimlerin yüksek aktivitesine neden olarak oksidatif stresi azaltmaktadır (Saletnik et al., 2022). Bu durum, bitkilerin oksidatif hasara karşı savunma mekanizmalarını güçlendirmektedir (Saletnik et al., 2022). Örneğin, Arabidopsis bitkilerinde SMF maruziyetinin köklerde H_2O_2 içeriğini önemli ölçüde azalttığı ve süperoksit dismutaz, katalaz ve peroksidaz gibi çeşitli antioksidan enzimlerin aktivitelerini artırdığı gözlemlenmiştir (Zhou et al., 2024). Bu artışların doku-spesifik olduğu ve bitkinin oksidatif strese karşı yanıtında önemli rol oynadığı belirlenmiştir (Zhou et al., 2024).

Şuman rezonans aralığındaki elektromanyetik alanlara maruz kalan buğday ve bezelye bitkilerinde katalaz ve süperoksit dismutaz aktiviteleri incelenmiş ve bu enzimlerin bitki redoks metabolizmasında önemli bir rol oynadığı gösterilmiştir (Mshenskaya et al., 2022). Düşük frekanslı manyetik alanlara dört saat boyunca 3 mT ve 10 mT şiddetinde maruz bırakılan bitkilerde katalaz ve askorbik peroksidaz aktivitesinin kök ve sürgün dokularında önemli ölçüde arttığı rapor edilmiştir (Tirono, 2022). Jeomanyetik alanın azaltılması da Arabidopsis thaliana'da ROS temizleyici enzimlerin metabolomik ve transkriptomik modülasyonuna yol açmaktadır (Parmagnani et al., 2022).

4.3 Fotosentetik Pigmentlerde Meydana Gelen Değişimler

Elektromanyetik alanlar ve manyetik alanlar, bitkilerin fotosentetik pigment içeriklerini ve dolayısıyla fotosentetik verimliliğini etkileyebilir (Schmidtpott et al., 2022). RF-EMF'ye maruz kalan marul bitkilerinde, fotosentetik verimlilikte önemli ve sistemik bir azalma gözlemlenmiştir (Tran et al., 2023). Alternatif elektromanyetik alanlara maruz kalan Arabidopsis thaliana'da yapılan bir çalışmada, fotosentetik parametrelerde belirgin farklılıklar kaydedilmiştir; bu durum ya düşük fotokimyasal sönümleme ya da plastokinon havuzunun daha yüksek indirgenmesi veya her ikisiyle ilişkilendirilmiştir (Schmidtpott et al., 2022). Transkriptom analizleri, EMF maruziyeti sonrasında transkript miktarlarında değişiklikler ve fotosentetik ile merkezi enerji metabolizmasındaki varyasyonlarla birlikte metabolit havuz boyutlarında yeniden düzenlemeler olduğunu göstermiştir (Schmidtpott et al., 2022).

Elektrik alan stimülasyonunun soya bitkilerinde klorofil içeriğini önemli ölçüde artırdığı, benzer bir etkinin fasulye bitkilerinde de gözlemlendiği belirtilmiştir (Dziwulska-Hunek et al., 2023). Ancak, yonca yapraklarında yapılan bazı çalışmalarda, elektromanyetik stimülasyonun klorofil a ve b konsantrasyonlarında azalmaya neden olduğu da rapor edilmiştir (Dziwulska-Hunek et al., 2022). Bu durum, pigment değişimlerinin tür ve uygulama koşullarına bağlı olarak farklılık gösterebileceğini düşündürmektedir. Statik manyetik alanlara maruz kalan marul fidelerinde tüm fotosentetik pigmentlerin, özellikle klorofil a'nın belirgin şekilde arttığı belirtilmiştir (Latef et al., 2020).

4.4 EMF ve Manyetik Alanların Stres Azaltıcı Rolleri

EMF ve manyetik alanların bitkilerdeki stres azaltıcı rolleri, antioksidan savunma sistemlerinin uyarılması ve hücresel adaptasyon mekanizmalarının etkinleştirilmesiyle ilişkilidir (Ayesha et al., 2023). SMF'lerin bitki fonksiyonlarını, büyümesini düzenlediği ve çevresel streslere karşı toleransı artırdığı belirtilmiştir (Radhakrishnan, 2019). SMF uygulaması, ROS oluşumunu hızlandırsa da antioksidan enzimlerin aktivitesini artırarak oksidatif stresi azaltmaktadır (Saletnik et al., 2022). Bu durum, bitkilerin stres altında hücre hasarını sınırlamasına yardımcı olur (Saletnik et al., 2022).

Manyetik alanların, bitki beslenmesini, su kullanım verimliliğini ve antioksidatif savunmayı iyileştirerek mahsul verimliliğini artırabileceğine dair bulgular mevcuttur (Ayesha et al., 2023). SMF'ye maruz kalma, bitkilerin ROS seviyesini düşürmesine ve antioksidan enzim aktivitesini ve nikotinamid birikimini artırarak oksidan dengesini sinerjik olarak sürdürmesine yardımcı olmaktadır (Zhou et al., 2024). Bu veriler, SMF'nin Arabidopsis thaliana'nın büyüme ve gelişimini, demir homeostazisini sürdürerek ve oksidatif stresi dengeleyerek düzenlediğini, bunun da bitki sağkalımı ve büyümesi için faydalı olabileceğini düşündürmektedir (Zhou et al., 2024). EMF'lerin fizyolojik süreçler üzerindeki etkileşimlerini anlamak, bitki verimliliğini artırmak ve çevresel streslere karşı direncini güçlendirmek için yeni stratejiler geliştirmeye olanak tanır (Schmidtpott et al., 2022). Manyetik alan uygulamaları, bitki büyümesini sürdürülebilir bir şekilde artırmak için modern tarımda giderek daha fazla kullanılmaktadır (Bellino et al., 2023).

5. STRES TOLERANS MEKANİZMALARI

Bitkiler, çevresel stres faktörlerine karşı çeşitli mekanizmalar geliştirmiştir ve elektromanyetik alanlar ile manyetik alanlar bu mekanizmaları etkileyerek stres toleransını değiştirebilmektedir.

5.1 Ca^{2+}, MAPK, CDPK Temelli Sinyal Yolları

Bitkilerde kalsiyum iyonları, çeşitli çevresel uyarılara verilen ilk yanıtlardan biri olan hızlı değişikliklerle stres sinyalizasyonunda önemli bir ikincil haberci görevi görür (Patra et al., 2021). Ca^{+2} sinyalleri, kalsiyum bağımlı protein kinazlar ve mitojenle aktive olan protein kinazlar gibi farklı protein kinazlar tarafından çözümlenir (Wurzinger et al., 2011). CDPK'ler, bitkilerdeki temel Ca^{+2} sensör gruplarını temsil eder ve çeşitli abiyotik ve biyotik streslere karşı adaptif yanıtları tetiklemek için özel Ca^{+2} imzalarını fosforilasyon olaylarına dönüştürür (Deepika et al., 2020). MAPK ve CDPK yolları, bitki hücrelerinde strese karşı hücresel metabolizmayı uyarlamak için birlikte çalışan iki ana yoldur (Wurzinger et al., 2011). Radyo frekanslı EMF maruziyeti, sitozolik kalsiyum hareketini ve reaktif oksijen türleri oluşumunu etkileyerek hücresel yanıtları tetikleyebilir (Tran et al., 2023). Örneğin, 900 MHz radyasyona maruz kalan domates bitkilerinde calmodulin ve kalsiyum bağımlı protein kinaz seviyelerinde artış gözlemlenmiştir (Tran et al., 2023). Bu durum, EMF maruziyetinin Ca^{+2} sinyal yollarını etkilediğini ve bitkilerin stres tepkilerini modüle edebileceğini göstermektedir (Kaur et al., 2021). CDPK genlerinin ekspresyon seviyeleri ve kinaz aktiviteleri, çeşitli abiyotik stresler, patojen saldırısı ve gelişimsel ipuçlarından etkilenir (Kiselev & Dubrovina, 2025).

5.2 Stomatal Düzenleme

Stomalar, bitkilerin CO_2 alımını fotosentez için dengelemek ve yapraklardan su kaybını düzenlemek için çevresel uyaranlara karşı açılıp kapanarak önemli bir rol oynar (Zhang et al., 2024). Bu stomatal hareketler, kuraklık gibi abiyotik stres faktörlerinin etkilerini hafifletmede kritik bir öneme sahiptir (Matkowski & Daszkowska-Golec, 2023). Aşırı düşük frekanslı manyetik alanların, bitkilerin olumsuz faktörlere, özellikle de kuraklığa karşı direncini modüle edebileceği düşünülmektedir (Mshenskaya et al., 2023). Buğday bitkilerinde 14.3 Hz. frekanslı bir manyetik alanın transpirasyon ve fotosentez üzerindeki etkisi incelenmiş ve kuraklık yoğunlaşması sırasında fotosentez süreçlerinin aktivitesi, mahsul su stresi indeksi ve yaprak alanı gibi parametrelerde değişiklikler belirlenmiştir (Mshenskaya et al., 2023). Bu, manyetik alanların stomatal düzenlemeyi dolaylı yollarla etkileyerek bitkilerin su dengesini ve stres toleransını optimize etmeye yardımcı olabileceğini düşündürmektedir.

5.3 Pigment Stabilizasyonu

Fotosentetik pigmentler, bitkilerin ışık enerjisini toplama ve dönüştürme yeteneği için esastır ve stres koşulları altında bunların stabilitesi, bitkinin hayatta kalması için kritik öneme sahiptir.

Elektromanyetik stimülasyonun fotosentetik pigment sentezinde bozulmaya neden olabileceği belirtilmektedir (Dziwulska-Hunek et al., 2023). Bununla birlikte, elektrik alan stimülasyonunun soya fasulyesinde klorofil içeriğini önemli ölçüde artırdığı gözlemlenmiştir (Dziwulska-Hunek et al., 2023). Benzer şekilde, statik manyetik alanlara maruz kalan marul fidelerinde tüm fotosentetik pigmentlerin, özellikle klorofil a'nın belirgin şekilde arttığı bildirilmiştir (Latef et al., 2020). Ancak, yonca yapraklarında yapılan bazı çalışmalarda, elektromanyetik stimülasyonun klorofil a ve b konsantrasyonlarında azalmaya yol açtığı da rapor edilmiştir (Dziwulska-Hunek et al., 2022). Alternatif elektromanyetik alanlara maruz kalan *Arabidopsis thaliana*'da fotosentetik parametrelerde belirgin farklılıklar kaydedilmiştir; bu durum, ya düşük fotokimyasal sönümleme ya da plastokinon havuzunun daha yüksek indirgenmesi veya her ikisiyle ilişkilendirilmiştir (Schmidtpott et al., 2022). Bu sonuçlar, pigment stabilizasyonunun bitki türüne, EMF/MF'nin özelliklerine ve uygulama koşullarına bağlı olarak değişebileceğini göstermektedir.

5.4 Metabolik Adaptasyon Süreçleri

EMF ve manyetik alanlar, bitkilerin metabolik süreçlerini etkileyerek stres koşullarına adaptasyon yeteneklerini geliştirebilir. Statik manyetik alan uygulaması, reaktif oksijen türlerinin oluşumunu hızlandırsa da, antioksidan enzimlerin yüksek aktivitesine yol açarak oksidatif stresi azaltmaktadır (Saletnik et al., 2022). SMF'ye maruz kalma, bitkilerin ROS seviyesini düşürmesine ve antioksidan enzim aktivitesini ile nikotinamid birikimini artırarak oksidan dengesini sinerjik olarak sürdürmesine yardımcı olmaktadır (Zhou et al., 2024). Jeomanyetik alanın azaltılması, *Arabidopsis thaliana*'da ROS temizleyici enzimlerin metabolomik ve transkriptomik modülasyonuna ve H_2O_2 üretimine yol açmaktadır (Parmagnani et al., 2022). Transkriptom analizleri, EMF maruziyeti sonrasında transkript miktarlarında değişiklikler ve fotosentetik ile merkezi enerji metabolizmasındaki varyasyonlarla birlikte metabolit havuz boyutlarında yeniden düzenlemeler olduğunu göstermiştir (Schmidtpott et al., 2022). Bu adaptif değişiklikler, bitkilerin çevresel stres faktörlerine karşı direncini artırmak için metabolik yollarını yeniden programlamasını sağlamaktadır.

6. SONUÇLAR

Bu çalışma, elektromanyetik alanların ve manyetik alanların bitkisel biyosistemler üzerindeki karmaşık ve çok yönlü etkilerini inceleyerek, bu fiziksel faktörlerin bitki gelişimi ve stres toleransı üzerindeki düzenleyici rollerini ortaya koymaktadır.

Manyetik alanların tohum çimlenme süreçleri üzerinde belirgin düzenleyici etkileri olduğu gözlemlenmiştir. Özellikle manyetik alan uyarımı, tohum çimlenme hızı ve yüzdesi gibi çimlenme indekslerinde önemli artışlara yol açabilmektedir (El-Sayed, 2023). Bu etkiler, manyetik alanların tohumlardaki biyokimyasal süreçleri ve protein/enzim aktivitelerini uyarmasıyla ilişkilendirilmektedir (Dziwulska-Hunek et al., 2023). Ayrıca, manyetik alanlar tohum kabuğunun geçirgenliğini artırarak su alımını kolaylaştırabilir (Tomeková et al., 2023), bu da çimlenmeyi teşvik eden önemli bir mekanizmadır (Kornarzyński et al., 2020). Fide gelişimi ve kök mimarisi üzerindeki olumlu etkiler, statik manyetik alanların kök büyümesini teşvik etmesi ve iyon kanallarının geçirgenliğini optimize etmesiyle açıklanmaktadır (Islam et al., 2020; Zhou et al., 2024).

EMF ve manyetik alanlar, bitkilerin abiyotik stres faktörlerine karşı geliştirdiği fizyolojik ve biyokimyasal yanıtları modüle ederek stres tolerans mekanizmalarına önemli katkılar sağlamaktadır. Bu alanlara maruz kalma, bitkilerde reaktif oksijen türleri metabolizmasını ve sitozolik Ca^{+2} seviyelerini etkileyerek hücresel tepkileri tetikleyebilir (Kaur et al., 2021). Statik

manyetik alanlar, ROS birikimini hızlandırsa da, antioksidan enzimlerin (katalaz, süperoksit dismutaz, peroksidaz gibi) aktivitesini artırarak oksidatif stresi azaltmaktadır (Saletnik et al., 2022; Zhou et al., 2024). Bu durum, bitkilerin hücresel hasarı sınırlamasına ve strese karşı direncini güçlendirmesine yardımcı olmaktadır (Saletnik et al., 2022). Fotosentetik pigmentlerde (klorofil a, b) meydana gelen değişimler, EMF maruziyetinin fotosentetik verimliliği etkileyebileceğini göstermekle birlikte (Schmidtpott et al., 2022), statik manyetik alanların klorofil içeriğini artırarak fotosentetik kapasiteyi iyileştirebileceği de belirtilmiştir (Latef et al., 2020). Ca^{+2}, MAPK ve CDPK temelli sinyal yollarının aktivasyonu, bitkilerin stres sinyallerini algılaması ve bunlara yanıt vermesinde kilit rol oynamakta olup, EMF'lerin bu yolları etkileyerek stres adaptasyonunu modüle edebileceği düşünülmektedir (Tran et al., 2023; Wurzinger et al., 2011).

EMF ve manyetik alanların bitki fizyolojisi üzerindeki bu düzenleyici etkileri, biyosistem tabanlı üretimde önemli potansiyel uygulamalar sunmaktadır. Manyetik olarak işlenmiş suyun kullanımı, çimlenme ve fide parametrelerini, büyüme ve verimi iyileştirerek tarımsal verimliliği artırabilmektedir (Selim et al., 2022). Manyetik alanların tohum çimlenmesi, bitki beslenmesi, su kullanım verimliliği ve antioksidatif savunmayı iyileştirerek mahsul verimliliğini artırabileceği bulguları (Ayesha et al., 2023), bu teknolojilerin sürdürülebilir tarım uygulamalarında değerlendirilebileceğini göstermektedir (Bellino et al., 2023). Özellikle, çevresel stres faktörlerine karşı bitki toleransını artıran bu mekanizmalar, iklim değişikliği ve azalan tarım alanları gibi küresel zorluklara karşı mücadelede yeni stratejiler sunabilir.

Gelecek Araştırmalar İçin Öneriler

EMF ve manyetik alanların bitkiler üzerindeki etkileri konusunda daha derinlemesine bilgi edinmek için gelecekteki araştırmalar aşağıdaki alanlara odaklanabilir:

- **Moleküler Mekanizmaların Detaylı İncelenmesi**: Alanların iyon kanalları, membran potansiyelleri, gen ekspresyonu ve protein sentezi üzerindeki spesifik moleküler mekanizmalarının ileri düzeyde araştırılması gerekmektedir (Kornarzyński et al., 2020).

- **Doz-Tepki İlişkilerinin Optimizasyonu**: Farklı bitki türleri için optimum frekans, şiddet ve maruz kalma süresi gibi parametrelerin belirlenmesi, tarımsal uygulamalarda etkinliği artıracaktır (Jo et al., 2024).

- **Uzun Vadeli Etkilerin Değerlendirilmesi**: EMF/MF maruziyetinin bitkilerin tüm yaşam döngüsü boyunca ve sonraki nesiller üzerindeki uzun vadeli etkilerinin incelenmesi önemlidir.

- **Çoklu Stres Faktörleri ile Etkileşimler**: Tek başına EMF/MF etkileri yerine, kuraklık, tuzluluk, ağır metal stresi gibi diğer abiyotik stres faktörleri ile birleştiğinde ortaya çıkan sinerjik veya antagonistik etkilerin araştırılması gerekmektedir (Radhakrishnan, 2019).

- **Gelişmiş Alan Uygulama Teknolojileri**: Tarımsal uygulamalar için daha verimli, ölçeklenebilir ve enerji açısından optimize edilmiş elektromanyetik alan uygulama sistemlerinin geliştirilmesi ve test edilmesi.

Bu öneriler, elektromanyetik alanların bitkisel biyosistemler üzerindeki potansiyelini tam olarak anlamak ve sürdürülebilir tarımda yenilikçi çözümler geliştirmek için bir yol haritası sunmaktadır.

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TOHUMLARDA FIZIKO-MEKANIK TARIMSAL ÜRETIM, İŞLEME TEKNOLOJILERI VE KALITE STANDARTLARI ÜZERINDEKI ETKISI

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ÖZET

Tohumların fiziko-mekanik özellikleri ekimden hasat dönemine, ürün işlemeden depolamaya kadar uzanan üretim periyodunun sağlıklı bir şekilde yürütülmesi için bilinmesi gereken en temel konulardan biridir. Tohumların fiziksel ve mekanik özelliklerini dikkate alarak ekim makinalarında kullanılan farklı ekici düzenler tasarlanmaktadır. Ayrıca özellikle biçerdöverlerin sarsak ve batör-kontrbatör aralıklarının dizayn edilmesinde tohumların fiziksel ve mekanik özelliklerden yararlanılmaktadır. Buna ilaveten hasat işleminden sonra sınıflandırma amacıyla kullanılan elek tasarımlarında da tohumların hem boyut hem de geometrik yapıları dikkate alınmaktadır. Bu sayede hasat sonrası kalite sınıflandırılması da hassas ve doğru bir şekilde yapılabilmektedir. Ürün depolama aşamasında da tohumların bu özelliklerinden yararlanılmaktadır. Depolama işleminde, tohumları hacim ağırlıkları ve nem düzeyleri bu parametreler arasında ön sırada yer almaktadır. Buna ilaveten kırılma, ezilme gibi mekanik özellikler de farklı makina tasarımlarında dikkate alınan temel bileşenler arasındadır. Son yıllarda tohumların bu özelliklerini dikkate alınarak yapılan çalışmalarda özellikle görüntü işleme tabanlı algoritmalar ve farklı yapay zekâ tahmin yöntemlerinden yararlanılmaktadır. Bu sayede zor ve zaman alıcı birçok işlem saniyeler içinde tamamlanmakta ve bu esnada insan faktörlü yanlışlarında önüne geçilmektedir. Bu amaç doğrultusunda yapılan araştırmaların çoğunda tohumların boyut özellikleri ve nem içeriklerinden yola çıkılarak kırılma direnci gibi mekanik özellikleri yüksek doğrulukla modellenebilmektedir. Ayrıca tohumlarının fiziksel ve mekanik özelliklerine dayalı olarak geliştirilen karar destek sistemleri; hassas ekim, enerji verimliliği yüksek kurutma teknolojileri, kontrollü depolama ve ileri kalite sınıflandırma uygulamaları içinde kullanılmaktadır. Bu modeller ıslah çalışmalarında etkin bir şekilde kullanılmaktadır. Bu bütüncül yaklaşım, sürdürülebilir tarımsal üretimin ve endüstriyel gıda güvenliğinin gelecekteki anahtar bileşenlerinden biri olacaktır. Bu çalışmada tohumların boyut, şekil, yoğunluk, sertlik ve kırılma dirençleri gibi fiziksel ve mekanik özelliklerin tarımsal üretim sürecindeki etkileri incelenmiştir. Ayrıca hasat sonrası yapılacak iş ve işlemlerde bu özelliklerden nasıl yararlanıldığı detaylıca analiz edilmiştir.

Anahtar Kelimeler: Tohum, fiziksel özellikler, mekanik dayanım, hasat sonrası işleme, kalite

THE EFFECT OF PHYSICAL-MECHANICAL AGRICULTURAL PRODUCTION, PROCESSING TECHNOLOGIES, AND QUALITY STANDARDS ON SEEDS

ABSTRACT

The physical and mechanical properties of seeds are essential factors to understand for smooth operation throughout the entire production process, from planting to harvest, processing, and storage. Different seeding arrangements used in planting equipment are designed considering these properties. Additionally, the physical and mechanical characteristics of seeds are taken into account when designing the spacing of concaves and counter-concaves in combine harvesters. Moreover, seed size and geometric structure are important for designing sieves used in classification after harvesting to ensure accurate and reliable quality assessment. These seed traits also influence storage, where parameters like volume weight and moisture content are critical. Mechanical properties, such as resistance to breakage and crushing, are fundamental in designing various machinery. In recent years, research on these seed characteristics has often utilized image processing algorithms and artificial intelligence prediction methods, enabling many complex and time-consuming tasks to be completed in seconds and reducing human error. Most studies indicate that properties like resistance to breakage can be accurately modeled based on seed size and moisture levels. Furthermore, decision support systems based on these properties are used in precision planting, energy-efficient drying, controlled storage, and advanced quality grading. These models are also valuable in breeding programs. This comprehensive approach will be vital for sustainable agriculture and food safety in the future. This study examines how seed physical and mechanical properties—such as size, shape, density, hardness, and fracture resistance—affect the agricultural production process. It also provides a detailed analysis of how these properties are applied during post-harvest operations and procedures.

Keywords: Seed, physical properties, mechanical strength, post-harvest processing, quality

1. GİRİŞ

Tohumlar, küresel gıda güvenliği ve sürdürülebilir tarımsal sistemlerin temelini oluşturan önemli bir tarımsal girdi olarak kabul edilmektedir (Sundareswaran et al., 2023). Dünya nüfusunun artışıyla birlikte gıda ihtiyacının karşılanması noktasında, yüksek kaliteli tohum kullanımı tarımsal üretimin artırılmasında vazgeçilmez bir unsurdur. Nitekim, bitkisel üretimin temelini oluşturan tohum kalitesi, herhangi bir başarılı tarım programının köşe taşını teşkil etmektedir. Tohum sektörü, çiftçilere kaliteli tohumlar sağlayarak gıda güvenliği açısından önemli bir role sahiptir. Kaliteli tohum kullanımı, standart uygulamalarla birleştiğinde, ürün verimini %15-20 oranında artırma potansiyeline sahiptir (Kumar et al., 2023). Bu bağlamda, tohumların genetik, fiziksel ve sağlık standartlarını karşılaması, arzu edilen ürün kalitesini ve verimliliğini belirleyen önemli faktörlerdendir (Tiwari & Park, 2024).

Tohumların fiziksel ve mekanik özellikleri; çimlenme, fide çıkışı ve genel fide canlılığı üzerinde doğrudan etkilere sahiptir (Blalogoe et al., 2020). Tohum boyutu, şekli ve iç yapısı; çimlenme performansını, canlılığı ve fide gelişimini önemli ölçüde etkiler. Örneğin, daha büyük tohumlar genellikle daha iyi tarla performansı ve fizyolojik kalite sergilemektedir. Tohum kabuğunun rengi, kalınlığı ve anatomik yapısındaki farklılıklar gibi fiziksel özellikler, su alımını ve tohum kabuğunun geçirgenliğini düzenleyerek çimlenme ve büyüme üzerinde belirleyici bir rol oynar (Upretee et al., 2024).

Mekanik özellikler ise tarım makinelerinin tasarımı ve işletilmesi açısından büyük önem taşımaktadır. Tohumların işlenmesi, ekim hassasiyeti ve hasat sonrası süreçlerde maruz kaldıkları mekanik stresler, tohum kalitesini ve ekim performansını doğrudan etkiler (Xue et al., 2019). Hasat ve işleme sırasındaki mekanik hasarlar, tohum canlılığını ve kalitesini olumsuz yönde etkileyebilir. Bu nedenle, tohumların fiziksel ve mekanik özelliklerinin anlaşılması, ekim teknolojilerinin geliştirilmesi ve tarımsal verimliliğin artırılması için önemlidir.

Tohum kalitesi ile tarımsal verimlilik arasında güçlü ve doğrudan bir ilişki bulunmaktadır. Tohum canlılığı, tarla koşullarında bitki gelişimi ve ürün verimliliği ile ilişkilendirilen temel bir fizyolojik özelliktir. Yüksek tohum canlılığı, tohumların çeşitli çevresel koşullar altında hızlı, homojen ve güçlü bir şekilde çimlenmesini ve fide oluşturmasını sağlayarak, ürün verimini ve kaynak kullanım verimliliğini doğrudan etkiler. Yüksek tohum canlılığı, zorlu çevre koşullarında hayatta kalmayı mümkün kılarak ekilebilir arazilerin verimliliğini artırır (Qiao et al., 2023).

Genel anlamda tohum kalitesi kavramı canlılık ve sağlık parametrelerini içermekte olup, yüksek verim elde etmenin ön koşuludur (Misra et al., 2023). Düşük tohum kalitesi, çimlenme oranını ve fide çıkışını azaltarak zayıf bitki gelişimi ve nihayetinde verim kaybına yol açabilir. Kaliteli tohum kullanımı; daha hızlı büyüme oranları, daha yüksek ekonomik getiriler ve daha değerli ürünler elde etmenin ilk adımıdır. Hasat ve kurutma tekniklerinin optimizasyonu da dahil olmak üzere tohum kalitesinin geliştirilmesi, tarımsal üretkenliği artırma potansiyeline sahiptir (Pedrosa et al., 2024).

Bu çalışma, tohumların tarımsal üretimdeki vazgeçilmez rolünü, fiziksel ve mekanik özelliklerinin bitki gelişimi ve ekim teknolojileri üzerindeki önemli etkilerini, ayrıca tohum kalitesi ile tarımsal verimlilik arasındaki doğrudan ilişkiyi mevcut literatür ışığında değerlendirmeyi amaçlamaktadır. Elde edilen bulgular, tohum bilimi ve teknolojisindeki güncel gelişmeleri gözden geçirerek, gelecekteki araştırma ve uygulamalar için bir çerçeve sunmaktadır.

2. TOHUMLARDA FİZİKSEL ÖZELLİKLER

Tohumların fiziksel özellikleri, bitki gelişimi, ürün verimi ve tarımsal işlemlerin verimliliği üzerinde önemli etkilere sahiptir. Bu özellikler, tohum kalitesinin değerlendirilmesinde ve tarımsal uygulamaların optimize edilmesinde kullanılabilecek parametreler sunar.

2.1 Boyut, Şekil ve Geometrik İndeksler

Tohum boyutu ve şekli, bitki gelişiminin ve ürün veriminin önemli belirleyicileri arasında yer almaktadır. Tohumun olgunluktaki boyutu, vejetatif büyüme üzerinde etkili olan önemli bir fiziksel kalite göstergesidir ve sıklıkla verimle ilişkilendirilir (Blalogoe et al., 2020). Büyük tohumlar, genellikle daha fazla karbonhidrat depoladıkları için fidelerin daha iyi bir başlangıç yapmasını ve tarlada daha iyi performans göstermesini sağlar. Örneğin, bazı çalışmalarda büyük tohumların daha yüksek çimlenme oranı ve çimlenme hızı sergilediği belirlenmiştir (Blalogoe et al., 2020). Ayrıca yapılan bazı araştırmalarda tohum boyutunun ve ağırlığının; bitki adaptasyonu, çevresel stres toleransı, verim ve kalite üzerinde önemli agronomik özellikler olduğu ifade edilmektedir (Boccaccini et al., 2024).

Tohumun uzunluğu, genişliği, alanı, çevresi ve ağırlığı gibi morfolojik ölçümler, tohum boyutunu ve şeklini belirlemek için kullanılan önemli parametrelerdir . Tohum şekli ve boyutu, su alımını (imbibisyon), tohum nem içeriğini ve dolayısıyla tohum çimlenmesini ve kalitesini etkileyebilir (Blalogoe et al., 2020). Tohumun dairesellik, yuvarlaklık gibi geometrik indeksleri, türlerin tanımlanması ve sınıflandırılması için önemli özelliklerdir (Cervantés et al., 2016). Dijital görüntü işleme sistemleri, tohum boyutu ve şeklinin otomatik olarak belirlenmesinde temel bir araç haline gelmiştir (Cervantés et al., 2016). Bu sistemler, tohumların geometrik figürlerle (daire, kardiyoit, elips vb.) karşılaştırılması yoluyla şeklinin hassas bir şekilde nicelleştirilmesine olanak tanır. Ayrıca, genotipler arasındaki farklılıkları veya gelişim evreleri boyunca meydana gelen değişimleri karşılaştırmak için kullanılabilirler.

2.2. Yüzey Alanı ve Özgül Alan

Tohumların yüzey alanı ve özgül yüzey alanı, su alımı ve gaz değişimi gibi fizyolojik süreçlerde önemli bir rol oynar (Mahajan et al., 2023). Su alımı, tohum çimlenmesinin başlangıcını işaret eden temel bir süreçtir ve tohumun hidrasyon durumu, metabolik aktivitenin yeniden başlaması için gereklidir. Tohum kabuğunun geçirgenliği, su alımını düzenleyen önemli bir faktördür ve tohumun yüzey özellikleri bu geçirgenliği etkiler (Upretee et al., 2024). Tohum iç kabuğunun porozite ağı, suyun tohum içine hareketini sağlayan önemli bir yapısal özelliktir (Mahajan et al., 2023).

2.3. Renk, Optik Özellikler ve Kalite İlişkisi

Tohum rengi ve optik özellikleri, tohum kalitesinin tahribatsız bir şekilde değerlendirilmesi için potansiyel bilgiler sunmaktadır (Nehoshtan et al., 2021). Tohum kabuğu rengi; tohum canlılığı, çimlenme, depolama ömrü ve streslere karşı direnç gibi fizyolojik süreçlerle ilişkilendirilmiştir. Örneğin, pigmentli tohumların, pigment içermeyen tohumlara göre daha yüksek çimlenme oranları ve canlılık gösterdiği ve depolama sırasında bozulmaya karşı daha dirençli olduğu bulunmuştur. Koyu renkli tohum kabukları, genellikle daha yüksek tohum sertliği ve fenolik bileşik içeriği ile ilişkilendirilir, bu da tohumu bozulmaya karşı korur ve canlılığını uzun süreli depolama boyunca sürdürmesine yardımcı olur (Jiamtae et al., 2022).

Optik teknolojiler ve yapay zekâ, yer fıstığı tohumlarının kalitesini belirlemede etkili yeni bilgiler sunmaktadır. RGB görüntüleme, renk, boyut, şekil ve yüzey dokusu gibi morfolojik verileri toplamak için kullanılmaktadır. Bunlara ilaveten hiper spektral görüntüleme, tohum

kalitesi ve güvenliğinin tahribatsız ve hızlı bir şekilde değerlendirilmesinde kullanılan yöntemler arasına girmiştir (Feng et al., 2019).

2.4. Nem İçeriğinin Fiziksel Özelliklere Etkisi

Tohumların nem içeriği, tohumun fiziksel ve mühendislik özelliklerini etkileyen en önemli parametrelerden biridir. Hasat ve hasat sonrası işlemler, depolama ve tohum işleme ekipmanlarının tasarımında nem içeriğinin kontrolü esastır (Hay et al., 2023). Nem içeriğindeki artış, tohum boyutunu artırabilir ve şeklini değiştirebilir.

Nem içeriği, tohumun mekanik hasara karşı direncini de belirler (Shahbazi et al., 2023). Yüksek nem içeriği, genellikle tohumun esnekliğini artırarak mekanik hasara karşı direncini azaltırken, çok düşük nem içeriği de kırılganlığı artırabilir. Ayrıca, nem içeriği, tohumun yoğunluğu, hacimsel ağırlığı gibi diğer fiziksel özelliklerini de etkiler (Moret-Fernández et al., 2023).

3. TOHUMLARDA MEKANİK ÖZELLİKLER

Tohumların mekanik özellikleri, tarımsal üretim süreçlerinde, özellikle hasat, işleme, taşıma ve ekim makinelerinin tasarımında büyük önem taşımaktadır. Bu özellikler, tohumun dış etkilere karşı direncini, hasar görme eğilimini ve genel performansını doğrudan etkiler.

3.1 Sertlik, Kırılma Direnci ve Elastikiyet

Tohumların sertliği, kırılma direnci ve elastikiyeti, hasat sonrası işlemler sırasında tohum bütünlüğünün korunması için önemli parametrelerdir. Bu özellikler, bir malzemenin kuvvet uygulaması sonucunda gösterdiği fiziksel özellikler olup, elastikiyet modülü, çekme mukavemeti ve sertlik gibi parametreleri içerir. Tohum kabuklarının sertliği, tohumu yırtıcılara karşı korur ve yüksek dayanıklılık, darbe direnci ve hiyerarşik çok işlevli yapılar gibi istenen mekanik özellikleri sergileyebilir (Flores-Johnson et al., 2018).

Kırılma direnci, tohumun işleme ve taşıma sırasında maruz kaldığı mekanik streslere dayanma kabiliyetini ifade eder. Bu direnç, tohumun nem içeriği, boyutu ve yönelimi gibi faktörlerden etkilenir. Pamuk tohumlarında yapılan çalışmalar, dikey olarak yönlendirilen tohumların yatay olanlara göre daha fazla basma kuvvetine dayandığını ve daha kuru tohumların daha yüksek kırılma direncine sahip olduğunu göstermiştir (Dowd et al., 2019).

3.2. Sürtünme Katsayısı ve Kayma Davranışı

Tohumların sürtünme katsayısı ve kayma davranışı, tarım makinelerinin tasarımı ve etkin çalışması için önemli mühendislik parametreleridir. Bu özellikler, tohumların ekim makineleri, taşıma sistemleri ve depolama tanklarındaki akışını, yığılma açısını ve genel hareketini etkiler. Örneğin, bir ekim makinesinden tohum akışı, tohumların fiziksel ve sürtünme özelliklerine bağlıdır (Harshavardhan et al., 2020).

3.3. Mekanik Özelliklerin Nem ve Sıcaklıkla Değişimi

Tohumların nem içeriği, hasat ve hasat sonrası işlemlerin mekanik özelliklerini etkileyen en önemli parametrelerden biridir. Mısır, pirinç ve soya fasulyesi üzerinde yapılan çalışmalar, nem içeriğindeki artışın tohum boyutunu artırdığını, şeklini değiştirdiğini ve kırılma kuvvetini etkilediğini göstermiştir.

Mısır tohumlarının basınç dayanımı ve gerinim özellikleri, nem içeriği ile doğrudan ilişkilidir. Yüksek nem içeriği, genellikle tohumu daha esnek hale getirerek mekanik hasara karşı direncini azaltabilirken, çok düşük nem içeriği de tohumu daha kırılgan hale getirebilir (Kruszelnicka et al., 2022). Yapılan bir araştırmada bambara çekirdeklerinin mukavemet özellikleri, nem içeriğine ve dane boyutuna bağlı olarak değiştiği; nem içeriği arttıkça kırılma mukavemetinin

azaldığı bildirilmiştir (Nwakuba et al., 2022). Kuru koşullarda, tohumlar daha yüksek kırılma direncine sahip olabilir (Dowd et al., 2019). Çevresel sıcaklık da tohumların mekanik hasar görme yüzdesini etkileyen bir faktördür (Shahbazi et al., 2023). Bu nedenle, tohum işleme ekipmanlarının tasarımı ve işletilmesi sırasında bu çevresel faktörlerin dikkate alınması, tohum kalitesinin korunması ve mekanik hasarın en aza indirilmesi için kritik öneme sahiptir.

4. FİZİKO-MEKANİK ÖZELLİKLERİN TARIMSAL ÜRETİME ETKİSİ

Tohumların fiziko-mekanik özellikleri, tarımsal üretim zincirinin çeşitli aşamalarında önemli bir rol oynamaktadır. Bu özellikler, ekimden çimlenmeye, kalite kontrolünden depolamaya kadar birçok süreci doğrudan etkileyerek tarımsal verimlilik ve sürdürülebilirlik üzerinde belirleyici bir etki yaratır.

4.1. Ekim Makinalarında Akışkanlık

Ekim makinelerinde tohum akışkanlığı ve tohum borularındaki davranışı, hassas ekimin başarısı için temel teşkil eder. Tohumların boyutu, şekli, yüzey pürüzlülüğü, yoğunluğu ve sürtünme katsayısı gibi fiziko-mekanik özellikleri, ekim mekanizmalarının tasarımını ve performansını doğrudan etkiler (Harshavardhan et al., 2020). Örneğin, tohumun sürtünme katsayısı ve kayma davranışı, ekim sırasında tohumların düşme hızını ve dağılımını belirler (Kaliniewicz et al., 2016). Düşük sürtünme katsayısına sahip, pürüzsüz yüzeyli tohumlar ekim borularında daha düzenli akış sergileyebilirken, yüksek sürtünme veya düzensiz şekle sahip tohumlar tıkanmalara ve düzensiz ekime yol açabilir.

Hassas ekicilerin geliştirilmesinde, tohumların geometrik ve sürtünme özelliklerinin anlaşılması büyük önem taşımaktadır (Guru et al., 2023). Özellikle mısır gibi düzensiz şekilli tohumlar için tasarlanan mekanik ekicilerde, tohum morfolojisinin ekim performansı üzerindeki etkisi dikkate alınmalıdır (Mao et al., 2024). Ayrık elemanlar yöntemi gibi simülasyon teknikleri, tohumların ekim makinesi içindeki hareketini modelleyerek, tohum yataklarına yerleşim performansını optimize etmek için kullanılmaktadır. Bu tür analizler, farklı tohum çeşitlerinin ekim makineleriyle uyumluluğunu değerlendirmek ve ekim hassasiyetini artırmak için mühendislik tasarımlarına ışık tutar.

4.2. Tohum Yatağında Yerleşim ve Çimlenme Performansı

Tohum yatağında optimum yerleşim, başarılı çimlenme ve fide gelişiminin ön koşuludur. Tohumun fiziksel özellikleri, tohum-toprak teması, su alımı ve gaz değişimi gibi çimlenmeyi etkileyen temel süreçlerde merkezi bir rol oynar. Tohumun boyutu ve yoğunluğu, ekim derinliği ve toprak partikülleriyle etkileşimi üzerinde etkilidir. Yeterli tohum-toprak teması, tohumun topraktan gerekli su ve oksijeni alabilmesi için hayati öneme sahiptir. Kötü yerleşim, hava boşluklarının oluşmasına neden olarak su alımını engelleyebilir ve çimlenmeyi geciktirebilir veya tamamen önleyebilir (Moret-Fernández et al., 2023).

Tohum yatağının nem içeriği, sıcaklığı ve toprak yapısı gibi çevresel faktörler, tohumun fiziksel özellikleri ile etkileşime girerek çimlenme performansını etkiler (Lamichhane et al., 2019). Örneğin, homojen boyutlara sahip bir tohum yatağı, tahıllarda hızlı ve tekdüze fide çıkışı için önemlidir (Balsari et al., 2020). Toprak parçacıkları arasındaki temas alanı ve toprak hidrolik iletkenliği gibi faktörler, tohumun su alım oranını doğrudan etkiler. Bu nedenle, tohum yatağının fiziksel özelliklerinin iyi yönetilmesi, homojen fide çıkışı ve yüksek verim için kritik öneme sahiptir (Lal et al., 2020).

4.3. Tohum Kabuk Sertliğinin İmbibisyon Üzerindeki Rolü

Tohum kabuğunun sertliği, tohumun su alımı (imbibisyon) üzerinde önemli bir etkiye sahiptir ve özellikle fiziksel uyku halinde olan tohumlarda çimlenmeyi kısıtlayıcı bir faktör olabilir (Mandizvo & Odindo, 2019). Sert tohum kabukları, suyun tohum içine nüfuz etmesini fiziksel olarak engelleyerek, tohumun çimlenme potansiyelini uzun süre korumasına neden olabilir (Pompelli et al., 2023). Bu durum, doğal ortamda tohumun olumsuz koşullardan korunmasına yardımcı olurken, tarımsal üretimde homojen çimlenmeyi engelleyebilir.

Tohum kabuğunun yapısı ve bileşimi, su alım hızını ve miktarını belirleyen önemli özelliklerdir . Örneğin, *Gleditsia sinensis* tohumlarında su geçirmez tohum kabuğu, çevresel adaptasyon için faydalı olsa da, çimlenmeyi engeller (Zhu et al., 2021). Benzer şekilde, bazı türlerde tohum kabuğu rengi ile tohum kalitesi (canlılık ve vigor) arasında ilişki olduğu belirtilmiştir (Mandizvo & Odindo, 2019). Koyu renkli tohum kabukları genellikle daha sert ve daha az geçirgen olup, bu da su alımını yavaşlatarak çimlenmeyi geciktirir. Bu durum, tohumun depolama ömrünü uzatsa da, ekim sonrası hızlı ve eşzamanlı fide çıkışını zorlaştırabilir.

5. Sonuçlar

Bu çalışma, tohumların fiziko-mekanik özelliklerinin tarımsal üretimdeki temel önemini ve bu özelliklerin modern tarım teknolojileriyle nasıl entegre edilebileceğini vurgulamıştır.

Tohumların boyut, şekil, yoğunluk ve nem içeriği gibi fiziksel özellikleri, çimlenme ve fide gelişimini doğrudan etkileyen kritik parametrelerdir. İri tohumlar, genellikle daha yüksek çimlenme oranları ve güçlü fide gelişimi sergileyerek tarımsal verimlilik için bir temel oluşturur. Mekanik özellikler ise hasat, ürün işleme ve ekim süreçlerinde tohumun bütünlüğünü korumak için bilinmesi gereken parametrelerdir. Bu özellikler, ekim makinelerinin hassasiyetini, depolama sırasında kalite kaybını ve hasat sonrası mekanik hasarı belirler. Çevresel stres koşulları altında tohumların fiziko-mekanik özelliklerindeki değişimler, çimlenme performansını olumsuz etkileyebilir ve bu nedenle dayanıklı çeşitlerin geliştirilmesi için bu etkileşimlerin anlaşılması büyük önem taşır.

Tohumların fiziko-mekanik özellikleri, temizleme, sınıflandırma, depolama ve değirmencilik gibi hasat sonrası işleme teknolojilerinin tasarımında ve optimizasyonunda temel girdiler sağlar. Boyut ve yoğunluk bazlı ayırma sistemleri, tohum partilerinin kalitesini artırmak için tohumların fiziksel farklılıklarından yararlanır. Ekim makineleri, tohumların akışkanlık ve sürtünme özelliklerine göre tasarlanarak hassas bir ekimin yapılması sağlanır. Modern işleme tesislerinde, mekanik hasarı en aza indirmek ve tohum kalitesini korumak için tohumların darbe dayanımı ve kırılma limitleri gibi mekanik özellikleri de dikkate alınmalıdır.

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E-TİCARET TESLİMAT SÜRESİ TAHMİİNİNDE DERİN ÖĞRENME YAKLAŞIMLARININ KARŞILAŞTIRILMASI: MLP, LSTM VE CNN MODELLERİ ÜZERİNE BİR UYGULAMA

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ÖZET

E-ticaret sektöründe teslimat süresinin doğru ve güvenilir biçimde tahmin edilmesi, müşteri memnuniyetinin artırılması, operasyonel kaynakların etkin yönetilmesi ve işletmelerin rekabet gücünün korunması açısından stratejik bir önem taşımaktadır. Artan sipariş hacmi ve değişken operasyonel koşullar, geleneksel tahmin yöntemlerinin yetersiz kalmasına neden olmakta; bu durum yapay zekâ ve özellikle yapay sinir ağlarına dayalı modellerin kullanımını gerekli kılmaktadır. Bu çalışma, Multilayer Perceptron (MLP), Long Short-Term Memory (LSTM) ve Convolutional Neural Network (CNN) olmak üzere üç farklı yapay sinir ağı mimarisinin e-ticaret teslimat süresi tahminindeki performansını karşılaştırmalı olarak analiz etmektedir. Modelleme sürecinde hazırlık süresi, teslimat mesafesi, trafik yoğunluğu, hava durumu, araç türü ve sipariş zamanı gibi operasyonel değişkenleri içeren gerçek bir lojistik veri seti kullanılmıştır. Python ortamında TensorFlow, Keras ve scikit-learn kütüphaneleri ile eğitilen modeller, %80 eğitim ve %20 test veri ayrımıyla değerlendirilmiştir. Performans analizinde Ortalama Mutlak Hata (MAE), Kök Ortalama Kare Hata (RMSE) ve R^2 katsayısı temel alınmıştır. Bulgular, MLP modelinin MAE=4,11 dakika, RMSE=5,17 dakika ve R^2=0,85 değerleriyle en başarılı modeli oluşturduğunu göstermektedir. LSTM modeli R^2=0,83, CNN modeli ise R^2=0,74 değeriyle daha düşük performans sergilemiştir. Korelasyon analizine göre teslimat süresini en fazla etkileyen değişkenler hazırlık süresi ve mesafedir. Sonuç olarak çalışma, MLP mimarisinin zaman bağımlılığı sınırlı veri yapılarında daha tutarlı çıktılar ürettiğini ve e-ticaret lojistiğinde karar destek süreçlerinde etkin bir araç olarak kullanılabileceğini ortaya koymaktadır.

Anahtar Kelimeler: Teslimat Süresi Tahmini, Yapay Sinir Ağı, Makine Öğrenmesi, E-Ticaret, Akıllı Lojistik Sistemleri.

COMPARATIVE ANALYSIS OF DEEP LEARNING APPROACHES IN E-COMMERCE DELIVERY TIME PREDICTION: AN APPLICATION OF MLP, LSTM, AND CNN MODELS

ABSTRACT

This study aims to improve inventory management in retail supply chains through data-driven decision support approaches. In the research, the K-Means clustering algorithm—an unsupervised machine learning method—was used to identify the relationships among product sales performance, inventory level, and order frequency. By grouping stock items based on their similar characteristics, the model enables businesses to maintain inventory balance and base their decision-making processes on quantitative data. The analysis was conducted using the Python 3.10 programming language within the Spyder IDE of the Anaconda distribution. Data loading, cleaning, and transformation processes were carried out with the Pandas and NumPy libraries, while modeling and performance evaluations were performed using the scikit-learn library. To determine the optimal number of clusters, the Elbow Method, Silhouette Coefficient, Davies–Bouldin Index (DBI), and Calinski–Harabasz Score (CH) were employed. According to the results obtained, k = 3 was identified as the most appropriate number of clusters. The model outputs revealed that the products were grouped into three main categories: Overstock, Balanced, and Understock. The model's Silhouette score of 0.3141, Inertia value of 101,751.79, low DBI, and high CH scores indicate that the clusters have a strong separation structure. The findings show that products in the balanced stock cluster can serve as a reference for replenishment policies, while the overstock group poses a capital-holding burden and the understock group carries a risk of lost sales. Overall, the K-Means algorithm stands out as an effective and applicable analytical method for inventory optimization, cost reduction, and the development of decision support systems in the retail sector.

Keywords: Delivery Time Prediction, Artificial Neural Network, Machine Learning, E-Commerce, Smart Logistics Systems.

1.GİRİŞ

Günümüzde teknoloji, insan yaşamının hemen her alanında etkisini giderek artırmakta; bireylerin alışkanlıklarını, işletmelerin iş yapış biçimlerini ve toplumsal dinamikleri köklü biçimde dönüştürmektedir. Bu dönüşümün en belirgin biçimde gözlemlendiği alanlardan biri de e-ticaret sektörüdür. Dijital dönüşümle birlikte çevrimiçi alışveriş süreçlerinin hız, erişilebilirlik ve güven unsurları etrafında yeniden şekillenmesi, e-ticaret işletmelerine yenilikçi çözümler geliştirmeyi zorunlu kılmıştır. Özellikle dijital işlemlerin hızlı ilerlemesi, müşterilerin sipariş oluşturma anından teslimat sürecinin tamamlanmasına kadar geçen zamanda anlık bilgi ve hızlı hizmet beklentilerini artırmaktadır. Bu nedenle, çevrimiçi platformlardan verilen siparişlerin kısa sürede, doğru ve güvenilir biçimde ulaştırılması, firmalar açısından hem müşteri memnuniyetini sağlamada hem de rekabet üstünlüğü elde etmede kritik bir faktör hâline gelmiştir.

Bu bağlamda, teslimat süresinin doğru biçimde tahmin edilmesi yalnızca bir lojistik optimizasyon problemi olarak değil; aynı zamanda müşteri deneyimi yönetimi, stok planlama, rota optimizasyonu ve iş gücü dağılımı gibi birçok süreci doğrudan etkileyen çok boyutlu bir analiz alanı olarak öne çıkmaktadır. Örneğin, bir yemek siparişinin teslimat süresinin doğru tahmin edilmesi, hem müşterilerin memnuniyetini artırmakta hem de tedarik zinciri üzerindeki operasyonel yükü azaltmaktadır.

İnsanlar karar verme süreçlerinde geçmiş deneyimlerinden ve çevresel ipuçlarından yararlanırken, teknolojik sistemler de benzer şekilde veri analizine dayalı öğrenme mekanizmaları geliştirmektedir. Bu noktada yapay zekâ sistemleri, insanın karar verme süreçlerini modelleyen bir yapı olarak ortaya çıkmakta ve karmaşık problemlerin çözümünde güçlü bir araç sunmaktadır. Özellikle yapay sinir ağları (YSA), çok değişkenli ve dinamik veri ortamlarında öğrenme yeteneği sayesinde karmaşık ilişkileri modelleyebilmekte ve geleceğe yönelik yüksek doğrulukta tahminler üretebilmektedir.

Bu çalışmada, teslimat odaklı sektörlerde yapay sinir ağı tabanlı bir tahmin modelinin e-ticaret teslimat süresi üzerindeki öngörü gücü analiz edilmektedir. Modelleme sürecinde geçmiş teslimat kayıtları, hava durumu, ulaşım mesafesi, teslimat aracı bilgisi ve trafik yoğunluğu gibi değişkenler dikkate alınmış; Python programlama dili ve ilgili makine öğrenmesi kütüphaneleri kullanılarak eğitim ve test süreçleri yürütülmüştür. Çalışmanın temel amacı, geliştirilen modelin gerçek dünyadaki teslimat sistemleriyle uyum düzeyini incelemek ve elde edilen bulgular doğrultusunda sektörel uygulamalara katkı sunmaktır.

Araştırma Sorusu: E-ticaret teslimat süresinin tahmininde farklı yapay sinir ağı mimarileri (MLP, LSTM ve CNN) arasında doğruluk, kararlılık ve genellenebilirlik açısından anlamlı bir performans farkı var mıdır?

Araştırma Hipotezi (H_1): Multilayer Perceptron (MLP) mimarisi, zaman bağımlılığı sınırlı veri setlerinde LSTM ve CNN mimarilerine kıyasla daha yüksek doğruluk ve istikrarlı tahmin performansı göstermektedir. (H_0): MLP, LSTM ve CNN modelleri arasında e-ticaret teslimat süresi tahmini doğruluğu açısından anlamlı bir fark yoktur.

Mevcut literatür, e-ticaret teslimat süresi tahmini üzerine yoğunlaşsa da çalışmaların büyük bir kısmı ya tek bir makine öğrenmesi modeline odaklanmakta ya da zaman serisi tabanlı tahminler üzerinde sınırlı kalmaktadır. Derin öğrenme mimarilerinin (MLP, LSTM, CNN) aynı veri seti üzerinde sistematik biçimde karşılaştırıldığı kapsamlı çalışmalar oldukça sınırlıdır. Ayrıca, çevrimiçi teslimat süreçlerinde operasyonel faktörlerin (hazırlık süresi, trafik, mesafe, hava durumu vb.) etkisini bütüncül biçimde ele alan modelleme yaklaşımlarının azlığı dikkat çekmektedir. Bu çalışma, söz konusu boşluğu doldurarak farklı derin öğrenme mimarilerinin e-

ticaret teslimat süresi tahminindeki göreli başarımını karşılaştırmalı olarak ortaya koymayı amaçlamaktadır.

2. LİTERATÜR ARAŞTIRMASI

Son yıllarda e-ticaret ve lojistik sektörlerinde tahminleme süreçlerinde yapay zekâ ve makine öğrenmesi tabanlı yöntemlerin kullanımı hızla artmıştır. Bu yaklaşımlar, yalnızca operasyonel süreçleri optimize etmekle kalmayıp, müşteri deneyimini iyileştiren karar destek sistemlerinin geliştirilmesine de önemli katkılar sunmaktadır.

Liu, Wang, Li, Payne, Yue ve Man (2024), e-ticaret platformlarında doğru ürün seçimini desteklemek amacıyla satış tahmini ve ürün seçimini entegre eden bir model geliştirmiş; altı farklı makine öğrenmesi yöntemini birleştirerek daha yüksek doğruluk elde etmiştir. Abed (2024) ise 47 çevrimiçi mağazadan 413 günlük veriyle yürüttüğü çalışmada, talep tahmininde hibrit modellerin e-ticaretin dinamik veri yapılarıyla başa çıkmada etkili olduğunu göstermiştir. Benzer şekilde Küp, Küp, Koçak, Yücekaya ve Hekimoğlu (2023), teslimat gecikmelerini gerçek zamanlı olarak öngören makine öğrenmesi modelleriyle operasyonel verimliliği ve müşteri memnuniyetini artırmıştır.

Teslimat süresi tahmini konusunda Salari, Liu ve Shen (2020), çevrimiçi perakendecilikte sipariş zamanı, ürün tipi, müşteri profili ve dağıtım merkezi yoğunluğu gibi değişkenlerle doğruluğu %40 oranında artıran maliyet duyarlı kuantil regresyon ormanları (CQRF) yaklaşımını önermiştir. Rokoss, Syberg, Tomidei, Hülsing, Deuse ve Schmidt (2024) ise küçük parti üretim yapan firmalarda teslimat süresini tahmin etmek için ANN, XGBoost ve SVM modellerini karşılaştırmış ve %50'ye varan doğruluk artışı elde etmiştir.

Atak, Kaya ve Arslanoğlu (2023) hava koşullarının konteyner terminal operasyonlarındaki yük elleçleme süresine etkisini analiz etmiş, çevresel değişkenlerin lojistik performans üzerindeki etkisini ortaya koymuştur. Nnaji, Collins, Omoraiyewa ve Joshua (2022), e-ticaret teslimat yönetiminde makine öğrenmesiyle gecikme risklerini önceden tahmin ederek müşteri memnuniyetini artırabilecek bir çerçeve sunmuştur. Yalçınkaya ve Hızıroğlu (2024), online yemek teslimatında sipariş zamanı, hava durumu ve trafik yoğunluğu gibi faktörleri dikkate alarak teslimat süresi tahmini için yüksek doğrulukta bir model geliştirmiştir. Karl (2022) tüketici iadelerinin tahmininde istatistiksel ve makine öğrenmesi tabanlı yöntemleri karşılaştırarak farklı tahmin senaryolarını değerlendirmiştir. Eichenseer, Hans ve Winkler (2025) ise iş gücü planlamasında teslimat pozisyonlarını beş gün önceden tahmin eden bir model geliştirerek aşırı veya yetersiz personel kullanımını azaltmıştır.

Bu çalışmalar genel olarak, derin öğrenme ve makine öğrenmesi temelli modellerin teslimat süresi tahmininde klasik istatistiksel yöntemlere göre daha başarılı sonuçlar ürettiğini göstermektedir. Özellikle özellik mühendisliği, hiperparametre optimizasyonu ve gerçek zamanlı veri entegrasyonu gibi gelişmiş tekniklerin, tahmin doğruluğunu anlamlı ölçüde artırdığı vurgulanmaktadır. Dolayısıyla yapay sinir ağı tabanlı modeller, akıllı lojistik sistemlerinde zaman planlaması ve kaynak yönetimi için stratejik bir karar destek aracı olarak değerlendirilmektedir.

3. MATERYAL VE METOT

3.1. Araştırma Yaklaşımı

Bu çalışma, e-ticaret sektöründe teslimat süresini etkileyen operasyonel değişkenleri dikkate alarak, farklı yapay sinir ağı mimarilerinin (MLP, LSTM, CNN) tahmin performanslarını karşılaştırmalı biçimde değerlendirmeyi amaçlayan nicel bir araştırma tasarımına sahiptir.

Çalışmada, deneysel modelleme yaklaşımı benimsenmiş ve farklı derin öğrenme modellerinin aynı veri seti üzerinde eğitim–test analizleri gerçekleştirilmiştir.

3.2. Veri Seti ve Değişkenler

Modelleme sürecinde kullanılan veri seti, gerçek lojistik operasyonlarını temsil edecek şekilde oluşturulmuştur. Veri setinde her bir gözlem, bir teslimat işlemine karşılık gelmektedir. Teslimat süresini (dakika cinsinden) etkilediği düşünülen altı bağımsız değişken belirlenmiştir:

Hazırlık Süresi (Prep_Time)

Mesafe (Distance_km)

Trafik Yoğunluğu (Traffic_Level)

Hava Durumu (Weather)

Araç Türü (Vehicle_Type)

Sipariş Saati (Order_Time)

Bağımlı değişken, teslimatın tamamlanma süresini ifade eden Teslimat Süresi (Delivery_Time)'dir. Veri seti, Excel formatında düzenlenmiş ve Python ortamına aktarılmıştır.

3.3. Veri Ön İşleme Süreci

Modelin başarımını olumsuz etkileyebilecek eksik, hatalı veya uç değerler temizlenmiş; veri bütünlüğü sağlanmıştır. Kategorik değişkenler (hava durumu, trafik yoğunluğu, araç türü) Label Encoding yöntemiyle sayısallaştırılmış, sayısal değişkenler ise farklı ölçeklerin etkisini ortadan kaldırmak için MinMaxScaler tekniğiyle [0,1] aralığında normalize edilmiştir. Veri seti, rastgele seçim yöntemiyle %80 eğitim ve %20 test olarak ikiye ayrılmış; modelin genellenebilirliğini test etmek amacıyla bu işlem 10 farklı tekrar (random seed varyasyonu) ile yürütülmüştür.

3.4. Model Mimarileri

Teslimat süresi tahmini için üç farklı yapay sinir ağı mimarisi kullanılmıştır:

Multilayer Perceptron (MLP): Tam bağlantılı katmanlardan oluşan klasik bir ileri beslemeli ağ yapısıdır. İki gizli katman (32 ve 16 nöron) içermekte olup, aktivasyon fonksiyonu olarak ReLU (Rectified Linear Unit) kullanılmıştır. Çıktı katmanı, doğrusal regresyon tahmini üreten tek nöronludur.

Long Short-Term Memory (LSTM): Zaman serisi veya ardışık veri yapılarındaki bağımlılıkları yakalamak amacıyla geliştirilmiş tekrarlayan sinir ağı (RNN) tabanlı bir modeldir. Bu çalışmada, veri setindeki sınırlı ardışıklık yapısına rağmen LSTM'nin performansı karşılaştırmalı olarak incelenmiştir.

Convolutional Neural Network (CNN): Genellikle uzamsal veri analizinde kullanılan bu model, girdi değişkenleri arasındaki lokal ilişkileri öğrenme yeteneği nedeniyle değerlendirmeye alınmıştır. Modelde bir konvolüsyon katmanı, bir "flatten" katmanı ve tam bağlantılı katmanlar kullanılmıştır.

Tüm modellerde Adam optimizasyon algoritması, Mean Squared Error (MSE) kayıp fonksiyonu ve Epoch=200 değerleri kullanılmıştır.

3.5. Performans Ölçütleri

Model performanslarının karşılaştırılmasında üç temel ölçüt kullanılmıştır:

Ortalama Mutlak Hata (MAE): Tahmin edilen ve gerçek değerler arasındaki mutlak farkın ortalaması, modelin genel hata düzeyini gösterir.

Kök Ortalama Kare Hata (RMSE): Hataların karelerinin ortalamasının karekökü alınarak büyük hataların etkisini daha güçlü biçimde yansıtır.

Açıklama Katsayısı (R^2): Modelin bağımlı değişken varyansını açıklama oranını ifade eder.

Elde edilen sonuçlar, her modelin 10 tekrarı üzerinden ortalama alınarak karşılaştırılmış ve en düşük hata değerini, en yüksek açıklama katsayısını sağlayan mimari en başarılı model olarak değerlendirilmiştir.

3.6. Analiz Ortamı

Tüm analizler Python 3.10 sürümü kullanılarak, Anaconda dağıtımı altında çalışan Spyder IDE ortamında gerçekleştirilmiştir. Kullanılan temel kütüphaneler arasında NumPy, Pandas, Matplotlib, scikit-learn, TensorFlow ve Keras yer almaktadır.

4. ANALİZ VE BULGULAR

Bu çalışmada, akıllı lojistik sistemlerinde teslimat süresinin tahminine yönelik bir yapay sinir ağı modeli geliştirilmiştir. Model, gerçek dünyadaki bir lojistik senaryosunu temsil eden veri seti kullanılarak oluşturulmuş ve teslimat süresi üzerinde etkili olduğu düşünülen operasyonel değişkenler (hazırlık süresi, mesafe, trafik durumu, hava koşulları, araç türü ve sipariş zamanı) dikkate alınmıştır. Çalışmanın temel amacı, bu değişkenlere dayalı olarak teslimat süresini dakikalık bazda tahmin eden bir derin öğrenme modelinin performansını değerlendirmektir.

Modelleme süreci Python programlama dili kullanılarak gerçekleştirilmiş; Pandas, NumPy, scikit-learn, TensorFlow/Keras ve matplotlib kütüphanelerinden yararlanılmıştır. Geliştirme ortamı olarak Anaconda ve Spyder IDE tercih edilmiştir. Veri seti Excel formatında hazırlanmış, ardından veri ön işleme aşamasına geçilmiştir. Bu aşamada kategorik değişkenler (hava durumu, trafik yoğunluğu, araç türü) Label Encoding yöntemiyle sayısallaştırılmış; sayısal değişkenler ise MinMaxScaler tekniğiyle normalize edilmiştir. Veriler, modelin öğrenme başarımını değerlendirmek amacıyla %80 eğitim ve %20 test olarak ikiye ayrılmıştır. Rastgele seçim yöntemiyle oluşturulan bu bölünme, modelin genellenebilirliğini test etmek üzere 10 kez tekrarlanmış ve her çalıştırmadan elde edilen sonuçlar raporlanmıştır.

Modelleme sürecinde üç farklı yapay sinir ağı mimarisi karşılaştırılmıştır: Multilayer Perceptron (MLP), Long Short-Term Memory (LSTM) ve Convolutional Neural Network (CNN). Her modelin giriş katmanını izleyen iki gizli katman (32 ve 16 nöron) kullanılmış, bu katmanlarda ReLU aktivasyon fonksiyonu tercih edilmiştir. Çıktı katmanı tek nöronlu olup, doğrusal regresyon çıktısı verecek şekilde yapılandırılmıştır. Tüm modellerde kayıp fonksiyonu olarak Mean Squared Error (MSE), optimizasyon algoritması olarak ise Adam kullanılmıştır.

Eğitim süreci tamamlandıktan sonra modeller test verisi üzerinde değerlendirilmiş ve performans göstergeleri olarak Ortalama Mutlak Hata (MAE), Kök Ortalama Kare Hata (RMSE) ve R^2 (açıklama katsayısı) değerleri hesaplanmıştır. Elde edilen sonuçlar Tablo 1, Tablo 2 ve Tablo 3'te sunulmuştur.

Değişkenler arasındaki ilişkileri görsel olarak analiz etmek amacıyla oluşturulan korelasyon matrisi Şekil 1'de verilmiştir. Sonuçlara göre "Prep_Time" (hazırlık süresi) ile "Delivery_Time" (teslimat süresi) arasında 0,52, "Distance_km" (mesafe) ile "Delivery_Time" arasında ise 0,68 düzeyinde pozitif korelasyon gözlemlenmiştir. Bu bulgular, teslimat süresinin özellikle hazırlık süresi ve mesafe değişkenlerinden güçlü biçimde etkilendiğini ortaya koymaktadır. Diğer değişkenlerin (hava durumu, trafik yoğunluğu ve araç türü) düşük

korelasyon değerlerine sahip olması, bu faktörlerin sınırlı etkiye sahip olduğunu göstermektedir.

Modellerin karşılaştırmalı performans analizine göre, MLP modeli hem hata metrikleri hem de açıklama gücü açısından en başarılı sonuçları vermiştir. MLP modelinin ortalama MAE değeri 4,11 dakika, RMSE değeri 5,17 dakika ve R^2 değeri 0,85 olarak ölçülmüştür. LSTM modeli %83 doğruluk (R^2=0,83) düzeyinde kalırken, CNN modeli en düşük performansı göstermiştir (R^2=0,74; RMSE=6,71). Bu farklılık, veri setinin zaman bağımlılığının sınırlı olmasından kaynaklanmaktadır. Ayrıca CNN modelinde gözlemlenen yüksek varyans, modelin karmaşık veriyi aşırı öğrenmeye eğilimli olduğunu göstermektedir.

Tablo 1. Modellerin MAE – Ortalama Mutlak Hata Değerlerinin Test Sonuçları

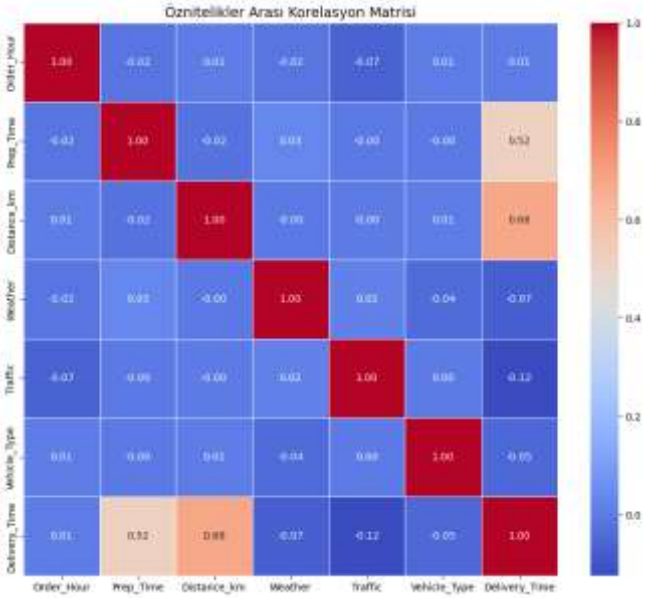
Model	**MAE - Ortalama Mutlak Hata**					**MAE -Mean Absolute Error**					
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Ortalama**
MLP	4,172	4,08	4,295	3,985	4,109	4,133	4,139	4,237	4,075	3,897	4,1122
LSTM	4,489	4,041	4,147	4,334	4,52	4,507	4,642	4,317	4,353	4,527	4,3877
CNN	6,557	6,907	5,803	4,658	4,895	4,516	5,028	6,739	4,468	4,33	5,3901

Tablo 2. Modellerin R^2 – Skor Belirleme Katsayısı Değerlerinin Test Sonuçları

Model	**R^2 Skor Belirleme Katsayısı**					**R-squared - Coefficient of Determination**					
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Ortalama**
MLP	0,85	0,852	0,842	0,861	0,851	0,85	0,856	0,849	0,853	0,861	0,8525
LSTM	0,823	0,858	0,849	0,834	0,824	0,829	0,813	0,844	0,846	0,825	0,8345
CNN	0,628	0,603	0,702	0,804	0,781	0,825	0,77	0,624	0,817	0,832	0,7386

Tablo 3. Modellerin RMSE - Kök Ortalama Kare Hata Değerlerinin Test Sonuçları

Model	**RMSE - Kök Ortalama Kare Hata**					**RMSE - Root Mean Squared Error**					
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Ortalama**
MLP	5,179	5,167	5,338	5,016	5,166	5,254	5,156	5,295	5,141	4,977	5,1689
LSTM	5,62	5,055	5,205	5,399	5,656	5,595	5,762	5,43	5,406	5,612	5,474
CNN	8,078	8,442	7,286	5,916	6,221	5,598	6,366	8,242	5,594	5,338	6,7081



Şekil 1. Öznitelikler Arası İlişki Matrisi

E-ticaret teslimat süresi tahmininde MLP mimarisi, doğruluk, kararlılık ve genellenebilirlik açısından en uygun model olarak öne çıkmıştır. Bu bulgular, yapay sinir ağı tabanlı modellerin lojistik süreçlerdeki teslimat süresi tahmininde etkili, uygulanabilir ve güvenilir bir karar destek mekanizması sunduğunu göstermektedir.

5. TARTIŞMA

Bu çalışmada elde edilen bulgular, literatürdeki önceki araştırmalarla büyük ölçüde uyum göstermekte ve e-ticaret teslimat süresi tahmininde yapay sinir ağı tabanlı modellerin yüksek doğruluk sağladığını desteklemektedir. Çalışmanın sonuçları, özellikle Multilayer Perceptron (MLP) mimarisinin, doğrusal olmayan ilişkileri etkin biçimde öğrenebilmesi sayesinde, klasik makine öğrenmesi algoritmalarına kıyasla daha istikrarlı tahminler üretebildiğini ortaya koymuştur. Bu durum, Liu ve ark. (2024) ile Abed (2024)'in çalışmalarında vurgulanan, hibrit ve ensembel öğrenme yaklaşımlarının e-ticaret süreçlerindeki karmaşık veri yapılarında daha yüksek tahmin başarısı sağladığı yönündeki bulgularla örtüşmektedir.

Elde edilen sonuçlar ayrıca, teslimat süresini etkileyen temel faktörlerin hazırlık süresi ve mesafe olduğunu göstermektedir. Bu bulgu, Yalçınkaya ve Hızıroğlu (2024)'nun çevrimiçi yemek teslimat sistemlerinde sipariş zamanı, trafik yoğunluğu ve mesafe gibi değişkenlerin teslimat tahmini doğruluğunda kritik rol oynadığı sonucuyla paraleldir. Benzer biçimde, Salari, Liu ve Shen (2020) tarafından önerilen maliyet duyarlı kuantil regresyon ormanları (CQRF) modeli de operasyonel değişkenlerin doğru biçimde modellenmesinin tahmin performansını önemli ölçüde artırdığını göstermiştir.

Bu çalışmada kullanılan veri setinde ardışık zaman bağımlılığının sınırlı olması, LSTM mimarisinin beklenenden düşük performans sergilemesine neden olmuştur. Bu durum, zaman serisi niteliği güçlü olan veri kümelerinde LSTM veya GRU gibi sıralı modellerin daha avantajlı olabileceğini gösteren literatürle (örneğin Rokoss ve ark., 2024) uyumludur. CNN modelinin düşük performansı ise, veri setinin uzamsal paternler içermemesiyle ilişkilendirilebilir. Benzer şekilde, Karl (2022) ve Eichenseer, Hans ve Winkler (2025) tarafından yürütülen çalışmalar da, model seçiminde veri yapısının belirleyici olduğunu vurgulamaktadır.

Çalışmanın bulguları, makine öğrenmesi tabanlı tahmin modellerinin lojistik operasyonlarda yalnızca teslimat süresini öngörmekle kalmayıp, operasyonel kaynak planlaması, rota

optimizasyonu ve müşteri bilgilendirme süreçlerine de doğrudan katkı sunabileceğini göstermektedir. Bu yönüyle araştırma, Küp ve ark. (2023) ile Nnaji ve ark. (2022)'nin lojistik süreçlerde gecikme öngörüsü ve müşteri memnuniyeti üzerine yaptığı çalışmalarla da örtüşmektedir.

Genel olarak bu çalışma, e-ticaret sektöründe MLP mimarisinin, hem doğruluk hem de genellenebilirlik açısından uygulanabilir bir tahmin aracı olduğunu ortaya koyarak literatüre özgün bir katkı sağlamaktadır. MLP modelinin basit yapısına rağmen yüksek açıklama gücü göstermesi, yapay sinir ağlarının karmaşık optimizasyon gerektiren lojistik süreçlerde güvenilir ve düşük maliyetli çözümler sunabileceğini göstermektedir. Ayrıca bu bulgular, gelecekte yapılacak araştırmalarda gerçek zamanlı veri akışlarının ve hibrit model kombinasyonlarının kullanılması durumunda tahmin başarısının daha da artırılabileceğine işaret etmektedir.

6. SONUÇ VE ÖNERİLER

Bu çalışmada, e-ticaret teslimat süresinin tahminine yönelik olarak geliştirilen üç farklı yapay sinir ağı mimarisi — Multilayer Perceptron (MLP), Long Short-Term Memory (LSTM) ve Convolutional Neural Network (CNN) — karşılaştırmalı olarak değerlendirilmiştir. Modellerin performansları, Ortalama Mutlak Hata (MAE), Kök Ortalama Kare Hata (RMSE) ve R^2 (açıklama katsayısı) metrikleri üzerinden analiz edilmiştir. Elde edilen sonuçlara göre, MLP modeli 4,11 dk MAE, 5,17 dk RMSE ve 0,85 R^2 değeriyle en yüksek doğruluk ve kararlılığı göstermiştir. LSTM modeli 0,83, CNN modeli ise 0,74 R^2 değeriyle daha düşük performans sergilemiştir. Bu bulgular, MLP mimarisinin zaman hassasiyetinin yüksek olduğu lojistik operasyonlarda güvenilir bir tahmin aracı olduğunu ortaya koymaktadır. Korelasyon analizi bulguları, teslimat süresini en çok etkileyen değişkenlerin hazırlık süresi (Prep_Time) ve mesafe (Distance_km) olduğunu göstermektedir. Bu değişkenlerin hedef değişkenle yüksek pozitif korelasyonu, MLP modelinin açıklayıcılık gücünü desteklemiştir. Diğer değişkenlerin etkisi sınırlı olsa da, yapay sinir ağlarının doğrusal olmayan ilişkileri öğrenebilme kapasitesi, modelin genel başarımını korumasını sağlamıştır. MLP mimarisi, e-ticaret teslimat süresi tahmininde en yüksek doğruluk ve genellenebilirliği sunarak diğer modellerden üstün performans göstermiştir. LSTM mimarisi, zaman bağımlı veri setlerinde daha güçlü performans gösterebilecek bir potansiyele sahip olsa da, bu çalışmada ardışık zaman ilişkisi bulunmadığından beklenen düzeyde başarı sağlayamamıştır. CNN modeli ise veri setinin uzamsal özellikler içermemesi nedeniyle düşük doğruluk elde etmiştir.

Bu bulgular doğrultusunda, gelecekteki çalışmalarda zaman serisi içeren daha büyük veri kümeleri kullanılarak LSTM ve GRU gibi ardışık veri odaklı modellerin performansları daha kapsamlı biçimde değerlendirilebilir. Ayrıca, gerçek zamanlı veri akışlarının (hava durumu, trafik yoğunluğu, anlık sipariş hacmi vb.) modele entegrasyonu, tahmin doğruluğunu artıracaktır. Hibrit yaklaşımların (örneğin MLP–XGBoost veya CNN–LSTM birleşimi) kullanımı ise farklı veri türlerinin bir arada işlendiği karmaşık lojistik senaryolarda daha yüksek genellenebilirlik sağlayabilir. Modelin çıktılarının rota optimizasyonu, kaynak planlama ve müşteri bilgilendirme sistemleriyle entegre edilmesi, akıllı lojistik sistemlerinde karar destek kapasitesini güçlendirecektir. Son olarak, farklı şehirler, sektörler veya teslimat türlerini içeren çoklu senaryo testleri ile modelin esnekliği, ölçeklenebilirliği ve pratik uygulanabilirliği artırılabilir. Geliştirilen MLP tabanlı model; e-ticaret lojistiğinde zaman planlaması, operasyonel kaynak tahsisi ve müşteri memnuniyetinin artırılması süreçlerinde etkili, güvenilir ve uygulanabilir bir karar destek aracı olarak değerlendirilmektedir. Artan veri çeşitliliği ve dijital entegrasyon olanaklarıyla birlikte, yapay zekâ tabanlı tahmin modellerinin akıllı lojistik sistemlerinde stratejik bir rol üstleneceği öngörülmektedir.

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VERİ ODAKLI KARAR DESTEK İÇİN K-MEANS KÜMELEME İLE ENVANTER OPTİMİZASYONU

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ÖZET

Bu çalışma, perakende tedarik zincirlerinde stok yönetiminin veriye dayalı karar destek yaklaşımlarıyla iyileştirilmesini amaçlamaktadır. Araştırmada, ürünlerin satış performansı, envanter seviyesi ve sipariş sıklığı arasındaki ilişkileri belirlemek üzere denetimsiz bir makine öğrenmesi yöntemi olan K-Means kümeleme algoritması kullanılmıştır. Model, stok kalemlerini benzer özelliklerine göre gruplandırarak işletmelerin stok dengesini sağlamalarına ve karar süreçlerini sayısal verilere dayandırmalarına olanak tanımaktadır. Analiz süreci, Python 3.10 programlama dili kullanılarak Anaconda dağıtımı içerisindeki Spyder IDE ortamında yürütülmüştür. Veri yükleme, temizleme ve dönüştürme işlemleri Pandas ve NumPy kütüphaneleri; modelleme ve performans değerlendirmeleri ise scikit-learn kütüphanesi ile gerçekleştirilmiştir. Optimum küme sayısının belirlenmesinde Elbow Yöntemi, Silhouette Katsayısı, Davies–Bouldin İndeksi (DBI) ve Calinski–Harabasz Skoru (CH) kullanılmıştır. Elde edilen sonuçlara göre, k = 3 değeri en uygun küme sayısı olarak belirlenmiştir. Model çıktıları, ürünlerin üç ana grupta toplandığını göstermiştir: Overstock (Aşırı Stok), Balanced (Dengeli Stok) ve Understock (Yetersiz Stok). Modelin Silhouette skoru 0,3141, Inertia değeri 101.751,79, düşük DBI ve yüksek CH skorları, kümelerin güçlü bir ayrım yapısına sahip olduğunu göstermektedir. Bulgular, dengeli stok kümesinde yer alan ürünlerin stok yenileme politikalarında referans olarak kullanılabileceğini; aşırı stok grubunda sermaye bağlanması, yetersiz stok grubunda ise satış kaybı riski bulunduğunu ortaya koymuştur. K-Means algoritması perakende sektöründe stok optimizasyonu, maliyet azaltımı ve karar destek sistemlerinin geliştirilmesi açısından etkili ve uygulanabilir bir analitik yöntem olarak öne çıkmaktadır.

Anahtar Kelimeler: K-Means kümeleme, stok yönetimi, veri madenciliği, karar destek sistemi, perakende sektörü, envanter optimizasyonu.

INVENTORY OPTIMIZATION THROUGH K-MEANS CLUSTERING FOR DATA-DRIVEN DECISION SUPPORT

ABSTRACT

This study aims to enhance inventory management within retail supply chains through data-driven decision-support approaches. The research employs the K-Means clustering algorithm, an unsupervised machine learning technique, to identify the relationships among product sales performance, inventory levels, and order frequency. By grouping inventory items based on their similar characteristics, the model enables firms to maintain stock balance and ground their decision-making processes in quantitative evidence.The analytical procedures were conducted using the Python 3.10 programming language within the Spyder IDE of the Anaconda distribution. Data loading, cleaning, and transformation operations were performed using the Pandas and NumPy libraries, while modeling and performance evaluation were executed with the scikit-learn library. To determine the optimal number of clusters, the Elbow Method, Silhouette Coefficient, Davies–Bouldin Index (DBI), and Calinski–Harabasz Score (CH) were employed. The results indicate that k = 3 represents the most appropriate number of clusters. Model outputs reveal that products are classified into three primary groups: Overstock, Balanced, and Understock. The Silhouette score of 0.3141, Inertia value of 101,751.79, along with a low DBI and high CH score, collectively demonstrate that the clusters exhibit a strong separation structure. The findings further indicate that items within the balanced stock cluster may serve as a benchmark for replenishment policies, while the overstock group presents risks related to excess capital allocation and the understock group entails the risk of potential sales loss.Overall, the K-Means algorithm emerges as an effective and applicable analytical method for inventory optimization, cost reduction, and the development of decision-support systems in the retail sector.

Keywords: K-Means clustering, inventory management, data mining, decision support system, retail sector, inventory optimization.

1.GİRİŞ

Dijitalleşme süreci, günümüz işletmelerinin üretimden tedarik zincirine, pazarlamadan müşteri ilişkilerine kadar tüm faaliyet alanlarını yeniden şekillendirmektedir. Endüstri 4.0 ve dijital dönüşüm yaklaşımlarıyla birlikte, üretim ve perakende sektörleri giderek daha fazla veri odaklı karar verme anlayışına yönelmektedir. Bu dönüşüm, yalnızca üretim hızını veya maliyet avantajını artırmayı değil; aynı zamanda stok yönetimi, müşteri memnuniyeti, tedarik planlama ve operasyonel verimlilik gibi alanlarda yüksek doğrulukta kararlar alınmasını da zorunlu kılmaktadır. Özellikle perakende sektörü, talep belirsizliği ve geniş ürün yelpazesi nedeniyle en karmaşık envanter planlama sorunlarının yaşandığı alanlardan biri olarak öne çıkmaktadır.

Perakende tedarik zincirlerinde karşılaşılan temel problemlerden biri, aşırı stok (overstock) veya yetersiz stok (understock) durumlarının dengelenememesidir. Aşırı stok, işletme sermayesinin atıl kalmasına, depolama maliyetlerinin artmasına ve ürünlerin değer kaybetmesine yol açarken; yetersiz stok, satış fırsatlarının kaçırılmasına ve müşteri memnuniyetsizliğine neden olmaktadır. Bu nedenle, stok seviyelerini doğru belirlemek ve optimize etmek, işletmeler açısından hem maliyet minimizasyonu hem de hizmet düzeyi maksimizasyonu bakımından stratejik bir gereklilik haline gelmiştir.

Bu noktada, veri bilimi ve makine öğrenmesi tabanlı yöntemler, geleneksel sezgisel yaklaşımlara kıyasla çok boyutlu analiz gücü sayesinde yöneticilere daha nesnel, tutarlı ve öngörülü bir bakış açısı kazandırmaktadır. Özellikle kümeleme (clustering) yöntemleri, stok kalemlerini benzer davranış ve performans özelliklerine göre gruplandırarak envanter stratejilerinin yeniden yapılandırılmasına olanak tanımaktadır. Bu yöntemler arasında öne çıkan K-Means algoritması, satış hacmi, stok düzeyi ve sipariş sıklığı gibi değişkenleri dikkate alarak ürünleri “benzer performans profillerine sahip kümeler” biçiminde sınıflandırmakta; böylece karar vericilere veri destekli, ölçülebilir ve uygulanabilir bir analiz çerçevesi sunmaktadır.

Bu çalışma, perakende sektöründe envanter optimizasyonu problemini K-Means kümeleme yöntemiyle ele almakta ve işletmelerin stok yönetimi süreçlerine veri tabanlı karar destek sistemi yaklaşımı getirmektedir. Araştırmanın temel amacı, satış, stok ve sipariş verilerini kullanarak stok kalemlerini üç ana küme (Aşırı Stok, Dengeli Stok, Yetersiz Stok) altında sınıflandırmak ve bu sınıflandırmanın işletmeler açısından sağlayabileceği operasyonel ve stratejik faydaları ortaya koymaktır. Analiz süreci, Python programlama dili ve bilimsel kütüphaneler (Pandas, NumPy, scikit-learn, Matplotlib) kullanılarak; veri ön işleme, modelleme, değerlendirme ve görselleştirme aşamalarında yürütülmüştür.

Elde edilen bulgular, veri destekli stok sınıflandırmasının işletmelerin maliyet azaltımı, talep karşılama oranı ve müşteri memnuniyeti gibi performans göstergelerini iyileştirebileceğini göstermektedir. Ayrıca önerilen model, küçük ve orta ölçekli işletmeler (KOBİ) için dijital dönüşüm sürecine entegre edilebilecek düşük maliyetli bir karar destek aracı olarak değerlendirilmektedir. Sonuç olarak, bu çalışma hem bilimsel literatüre katkı sunmakta, hem de uygulamaya dönük yapısıyla perakende sektöründe karar vericilere sürdürülebilir rekabet gücü kazandıracak bir yol haritası önermektedir.

2. LİTERATÜR ARAŞTIRMASI

Son yıllarda yapılan araştırmalar, envanter yönetimi ve stok optimizasyonu alanlarında veri madenciliği ve makine öğrenmesi tabanlı yöntemlerin işletmelere önemli ölçüde değer kattığını ortaya koymaktadır. Özellikle K-Means kümeleme algoritması, ürünleri benzer özelliklerine göre gruplandırarak envanter politikalarının optimizasyonunda, talep tahmininde ve maliyet azaltımında güçlü bir araç olarak öne çıkmaktadır. Literatürde bu yöntemin farklı sektörlerdeki

uygulamaları, K-Means'in esnek, ölçeklenebilir ve veri odaklı yapısı sayesinde geleneksel tek kriterli yöntemlere göre daha üstün sonuçlar verdiğini göstermektedir.

Wang, Hou ve Guo (2024), elektrikli araçlara hizmet veren batarya değişim ve şarj istasyonlarında (BSCS) belirsizlik altında envanter optimizasyonu için K-Means tabanlı Distributionally Robust Optimization (DRO) yaklaşımını geliştirmiştir. Çalışma, modelin enerji maliyetlerini düşürürken hizmet sürekliliğini artırdığını ve batarya stoğundaki dengesizlikleri minimize ettiğini ortaya koymuştur. Bu araştırma, K-Means algoritmasının belirsizlik yönetimi ve kaynak tahsisi süreçlerinde stratejik bir araç olabileceğini göstermektedir.

Lolli, Ishizaka ve Gamberini (2014), çok kriterli envanter sınıflandırması (MCIC) alanında Analitik Hiyerarşi Süreci (AHP) ile K-Means kümeleme yöntemini birleştirerek AHP-K-Veto modelini geliştirmiştir. Bu hibrit yaklaşım, bir ürünün yalnızca tek bir kritere göre değil, birden çok faktöre (maliyet, temin süresi, talep istikrarı vb.) dayalı olarak değerlendirilmesini sağlamış ve stokların önceliklendirilmesinde daha doğru sonuçlar elde etmiştir.

Kusrini (2015), perakende sektöründeki ürünleri satış sıklığı ve işlem değeri değişkenlerine göre K-Means yöntemiyle sınıflandırmış; bu sayede personel deneyimine dayalı sezgisel karar süreçlerini veri destekli bir yapıya dönüştürmüştür. Çalışma, dijital dönüşümün envanter yönetiminde nasıl somut çıktılar sağlayabileceğine dair önemli bir örnek teşkil etmektedir.

Khanorkar ve Kane (2023), ABC analizi, çok kriterli karar verme (MCDM) ve makine öğrenmesi tekniklerini entegre ederek hibrit bir stok sınıflandırma modeli önermiştir. Çalışmanın bulguları, K-Means algoritmasının sınıflandırma doğruluğu bakımından geleneksel yöntemlere kıyasla daha başarılı olduğunu ve büyük veri kümelerinde yüksek ölçeklenebilirlik sağladığını göstermiştir.

Balugani ve arkadaşları (2018), üretim tesislerinde K-Means ve Ward's kümeleme yöntemlerini karşılaştırmış; dönüştürülmüş özellikler (örneğin birim değer, talep varyansı, servis seviyesi) kullanıldığında K-Means modelinin envanter kontrolünde maliyet etkinliğini önemli ölçüde artırdığını belirtmiştir. Çalışma, kümeleme tabanlı analizlerin üretim planlama ve stok yenileme politikalarında karar destek sağlayabileceğini ortaya koymaktadır.

Naznin ve ark. (2024) ise küçük ölçekli işletmelerde müşteri tutundurma, finansal öngörü ve envanter optimizasyonu için farklı makine öğrenmesi algoritmalarını (Random Forest, Lasso, K-Means, ARIMA) karşılaştırmış ve her modelin belirli işlevlerde farklı avantajlar sunduğunu göstermiştir. Bu çalışmada K-Means algoritmasının özellikle envanter gruplandırma ve segment bazlı karar destek alanlarında etkili bir araç olduğu vurgulanmıştır.

Kusak ve çalışma arkadaşları (2021), K-Means ve Apriori birliktelik analizi yöntemlerini birleştirerek mekânsal veri madenciliğinde heyelan risk haritalaması gerçekleştirmiştir. Her ne kadar konu alanı farklı olsa da, çalışmanın bulguları K-Means'in çok boyutlu ve karmaşık veri kümelerinde yüksek doğruluk sağladığını ve coğrafi risk analizi gibi farklı alanlara da uygulanabilir olduğunu göstermektedir. Bu yönüyle K-Means'in genel amaçlı bir kümeleme aracı olarak esnekliğini vurgulamaktadır.

Porter (2018), savunma sanayisinde fazla stok problemini çözmek amacıyla K-Means tabanlı maliyet ve talep fonksiyonları geliştirmiştir. Model, envanter fazlasını %31 ve toplam maliyeti %34 oranında azaltarak, savunma lojistiğinde veri temelli karar verme yaklaşımının somut faydalarını ortaya koymuştur. Bu çalışma, K-Means'in yüksek değerli ve karmaşık tedarik zincirlerinde uygulanabilirliğini göstermektedir.

Prianus (2022), küçük ölçekli bir bilgisayar mağazasında satış verilerini K-Means algoritmasıyla analiz ederek stokları satış performansına göre sınıflandırmış ve web tabanlı bir karar destek sistemi geliştirmiştir. Bu sistem, manuel stok takibini ortadan kaldırarak işletmeye gerçek zamanlı stok yönetimi avantajı kazandırmıştır.

Purnamasari ve ark. (2023), KOBİ'lerde talep tahmini amacıyla K-Means tabanlı ürün sınıflandırmasını XGBoost, LSTM ve SARIMAX gibi gelişmiş tahmin modelleriyle karşılaştırmış; en düşük hata oranını XGBoost modelinin verdiğini tespit etmiştir. Ancak çalışmanın bulguları, K-Means algoritmasının ön sınıflandırma aşamasında kullanılmasının bu tahmin modellerinin başarısını anlamlı biçimde artırdığını göstermiştir.

Bu literatür incelemesi, K-Means algoritmasının yalnızca bir kümeleme aracı olmanın ötesinde, envanter yönetiminde stratejik karar destek, talep tahmini, maliyet azaltımı ve dijital dönüşüm süreçlerinde etkin bir rol oynadığını açık biçimde ortaya koymaktadır.

3. MATERYAL VE METOT

Bu çalışmada, perakende envanter verilerinin sınıflandırılması ve analiz edilmesi amacıyla denetimsiz bir öğrenme yaklaşımı olan K-Means Kümeleme Algoritması kullanılmıştır. Veri setinde yer alan her bir stok kaleminin durumu, "Inventory Level" (Envanter Seviyesi), "Units Sold" (Satılan Birimler) ve "Units Ordered" (Sipariş Edilen Birimler) değişkenleri temel alınarak üç boyutlu bir uzayda kümelendirilmiştir (k = 3).

Analiz öncesinde, değişkenler arasındaki ölçek farklılıklarının sonuçları etkilememesi için tüm veriler StandardScaler yöntemiyle standart ölçekleme işlemine tabi tutulmuştur.

Kümeleme sonucunda elde edilen merkezler (centroidler), envanter yönetimi açısından anlamlandırılabilmeleri için "Aşırı Stok Skoru (Overstock Score)" adı verilen sezgisel bir metrikle değerlendirilmiştir. Bu metrik, her bir kümenin ortalama stok, satış ve sipariş performansını temsil edecek şekilde hesaplanmış; böylece kümeler üç temel kategori altında sınıflandırılmıştır:

Overstock (Aşırı Stok): Yüksek stok düzeyine karşın düşük satış performansı gösteren ürünler,

Balanced (Dengeli Stok): Satış ve sipariş miktarları arasında denge bulunan ürünler,

Understock (Yetersiz Stok): Düşük stok düzeyine rağmen yüksek satış veya sipariş talebi gösteren ürünler.

Bu sınıflandırma, işletme yöneticilerine stok optimizasyonu, talep tahmini ve karar verme süreçlerinde veri odaklı bir temel sağlamaktadır. Kümeleme sonuçları hem özet istatistikler (ortalama, medyan) hem de iki ve üç boyutlu dağılım grafikleriyle görselleştirilerek sunulmuştur.

3.1. Veri Seti

Modelleme sürecinde kullanılan veri seti, gerçek perakende envanter operasyonlarını temsil edecek biçimde hazırlanmıştır. Her bir satır, bir stok kaleminin belirli bir dönem içindeki stok hareketini yansıtmaktadır.

Çalışmada analiz edilen üç temel değişken şunlardır: Inventory Level (Envanter Seviyesi): Belirli bir dönemde stokta bulunan ürün miktarı, Units Sold (Satılan Birimler): Aynı dönemde satılan ürün adedi, Units Ordered (Sipariş Edilen Birimler): Stok yenileme amacıyla verilen sipariş miktarı.

Bu çalışmada bağımlı değişken bulunmamakta olup, veriler doğal yapısına göre denetimsiz bir öğrenme yöntemi olan K-Means algoritmasıyla kümelendirilmiştir. Veri seti Excel formatında

düzenlenmiş, Python ortamına aktarılmış ve analiz öncesinde ölçek farklılıklarını ortadan kaldırmak amacıyla standartlaştırılmıştır.

Elde edilen kümeler, stok yönetimi açısından değerlendirilmiş ve "Aşırı Stok Skoru" üzerinden yorumlanmıştır.

3.2. Veri Ön İşleme Süreci

Veri ön işleme aşaması, ham verinin temizlenmesi, dönüştürülmesi ve K-Means algoritmasına uygun hale getirilmesi adımlarından oluşmaktadır.

İlk olarak, belirtilen Excel dosyası (retail_store_inventory_data.xlsx), pandas kütüphanesi kullanılarak Python ortamına aktarılmıştır. Değişken adlarındaki tutarsızlıklar giderilmiş, analizde kullanılacak üç temel değişkenin (Inventory Level, Units Sold, Units Ordered) veri setinde bulunduğu doğrulanmıştır. Bu alanlarda yer alan hatalı veya metin tabanlı veriler sayısal formata dönüştürülmüş, eksik veya geçersiz değerler içeren gözlemler veri setinden çıkarılarak veri bütünlüğü sağlanmıştır.

K-Means algoritması, gözlemler arasındaki Öklid mesafesi (Euclidean Distance) temelli bir modeldir; bu nedenle değişkenler arasındaki ölçek farkları modelin başarısını etkileyebilmektedir. Bu etkiyi gidermek için tüm sayısal değişkenler StandardScaler yöntemiyle normalize edilmiştir. Her bir değişkenin ortalaması 0, standart sapması 1 olacak biçimde dönüştürülmüş; böylece tüm değişkenler kümeleme sürecine eşit ağırlıkla dahil edilmiştir.

Bu işlemler sonucunda, eksik değerlerden arındırılmış, sayısal ve dengeli bir veri seti elde edilmiştir. Nihai veri matrisi (X_scaled), K-Means algoritmasının uygulanması için hazır hale getirilmiştir.

3.3. Performans Ölçütleri

Modelin performansını değerlendirmek için dört temel ölçüt kullanılmıştır:

Inertia (Within-Cluster Sum of Squares – WSS): Her gözlemin kendi küme merkezine olan uzaklığının kareleri toplamıdır. Düşük WSS değeri, kümelerin daha sıkı ve homojen olduğunu gösterir.

Silhouette Katsayısı: Her gözlemin ait olduğu kümeye yakınlığı ile diğer kümelere uzaklığını karşılaştırır. Değer aralığı -1 ile 1 arasındadır; 1'e yakın değerler iyi ayrışmış kümeleri ifade eder.

Davies–Bouldin İndeksi (DBI): Kümeler arasındaki benzerlik ile küme içi uzaklıkları değerlendirir. Düşük DBI değeri, kümeler arası ayrışmanın güçlü olduğunu gösterir.

Calinski–Harabasz (CH) Skoru: Kümeler arası varyansın, küme içi varyansa oranıdır. Yüksek CH değeri, kümelerin hem yoğun hem de iyi ayrılmış olduğunu belirtir.

Bu metrikler birlikte değerlendirilerek, modelin hem içsel tutarlılığı hem de kümeler arası ayrışma başarısı analiz edilmiştir. Optimum küme sayısının belirlenmesinde Elbow (Dirsek) Yöntemi ve Silhouette analizi birlikte kullanılmıştır.

3.4. Analiz Ortamı

Tüm veri ön işleme, modelleme ve görselleştirme adımları Python 3.10 programlama dili kullanılarak yürütülmüştür. Analiz süreci, bilimsel hesaplama ve veri bilimi uygulamaları için yaygın biçimde kullanılan Anaconda dağıtımı içerisindeki Spyder Entegre Geliştirme Ortamı (IDE) üzerinde gerçekleştirilmiştir.

Kullanılan başlıca kütüphaneler şunlardır: pandas; Veri yükleme, temizleme ve düzenleme, NumPy: Sayısal hesaplamalar, scikit-learn; K-Means kümeleme modeli ve performans ölçümleri, Matplotlib; Kümelerin iki ve üç boyutlu görselleştirilmesi.

Bu araçlar sayesinde elde edilen kümeleme sonuçları, hem istatistiksel olarak değerlendirilmiş hem de görsel olarak desteklenmiştir.

4. ANALİZ VE BULGULAR

Bu bölümde, stok yönetimi süreçlerinde ürünlerin satış performansı ile envanter seviyeleri arasındaki ilişkileri ortaya koymak amacıyla gerçekleştirilen K-Means kümeleme analizi ayrıntılı biçimde sunulmaktadır. Analiz süreci, Python 3.10 programlama dili kullanılarak Anaconda dağıtımı kapsamındaki Spyder IDE üzerinde yürütülmüştür.

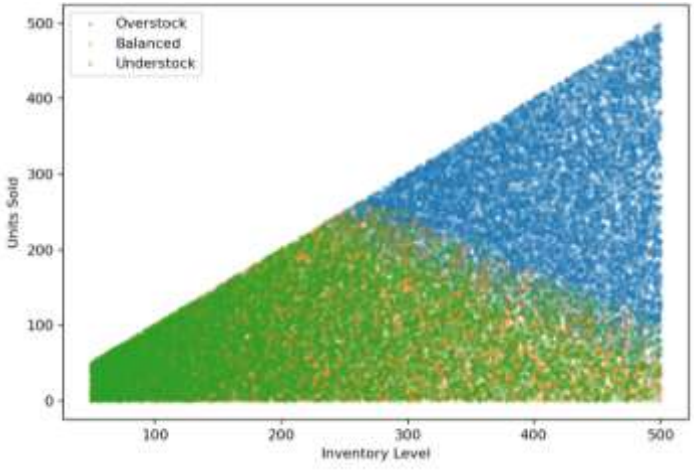
Veri yükleme, temizleme ve düzenleme işlemleri Pandas ve NumPy kütüphaneleri aracılığıyla gerçekleştirilmiş; kümeleme modeli, scikit-learn kütüphanesinin KMeans sınıfı kullanılarak oluşturulmuştur. Sonuçların iki ve üç boyutlu görselleştirmeleri ise Matplotlib kütüphanesi ile hazırlanmıştır. Bu bütünleşik analiz ortamı, veri hazırlama, modelleme ve yorumlama aşamalarının sistematik biçimde yürütülmesini sağlamıştır.

4.1. Küme Sayısının Belirlenmesi

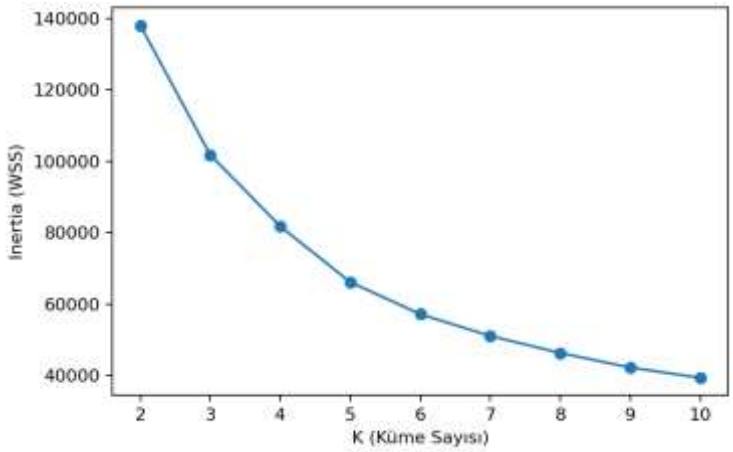
Modelde optimum küme sayısının belirlenmesi amacıyla dört farklı metrikten yararlanılmıştır: Elbow Yöntemi, Silhouette Katsayısı, Davies–Bouldin İndeksi (DBI) ve Calinski–Harabasz Skoru (CH).

Şekil 2–5'te gösterilen değerlendirme grafikleri incelendiğinde, Elbow Yöntemi sonucunda dirsek noktasının k = 3 değerinde belirginleştiği görülmüştür. Bu durum, modelin üç küme ile anlamlı bir ayrım düzeyi elde ettiğini göstermektedir.

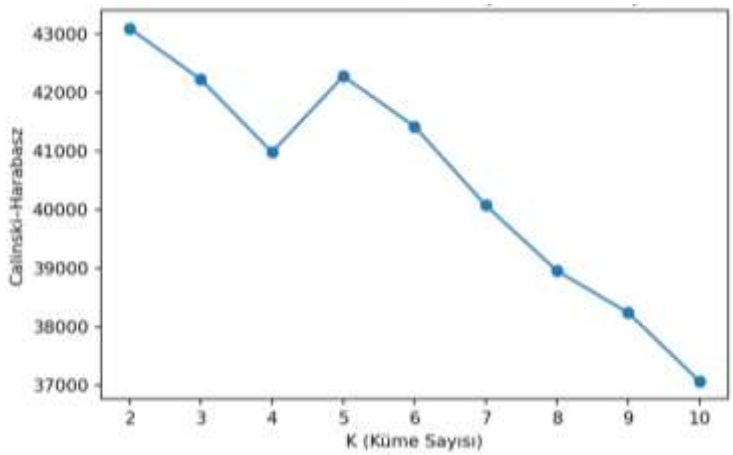
Ayrıca, Davies–Bouldin İndeksi'nin (Şekil 4) k = 3 için düşük bir değer alması, Calinski–Harabasz Skoru'nun (Şekil 3) aynı noktada maksimuma yakın çıkması ve Silhouette Katsayısı'nın (Şekil 5) 0,3141 olarak ölçülmesi; bu seçimin hem istatistiksel olarak anlamlı hem de yapısal olarak tutarlı olduğunu doğrulamaktadır. Bu bulgular, üç kümenin veri setindeki gözlemleri homojen biçimde gruplayabildiğini ve kümeler arası ayrışmanın makul düzeyde olduğunu göstermektedir.



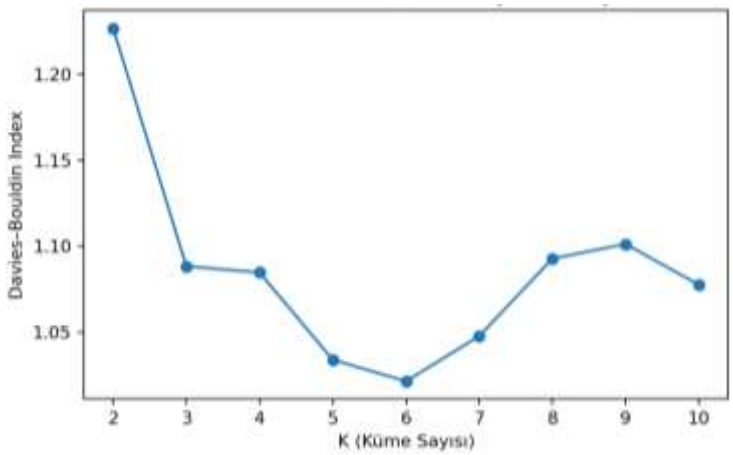
Şekil 1. K-Means (k=3) Sonuçları: Envanter–Satış Dağılımı



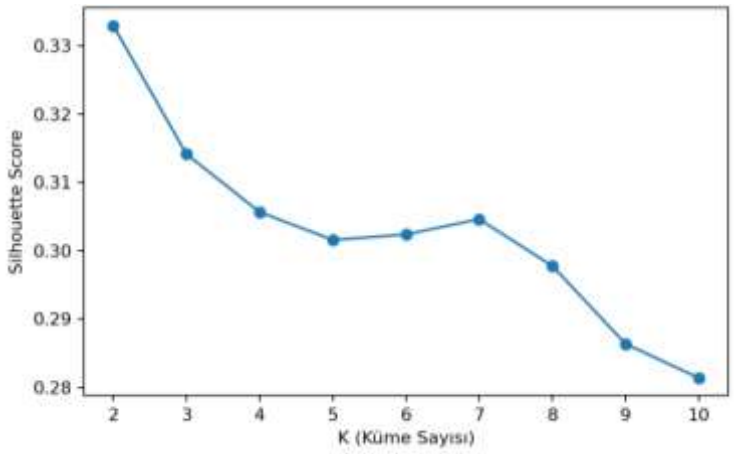
Şekil 2. Elbow Yöntemi (WSS vs K)



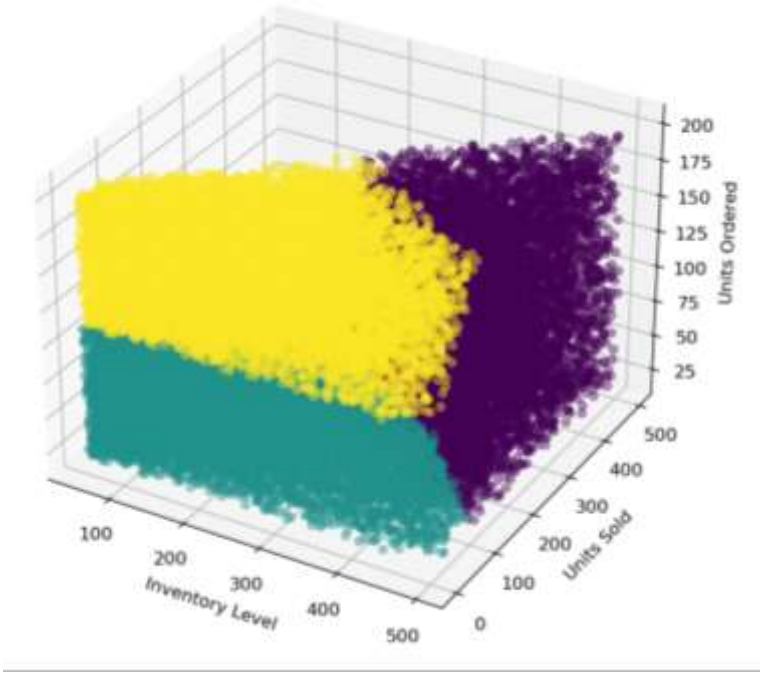
Şekil 3. Calinski–Harabasz Skoru (CH vs K)



Şekil 4. Davies–Bouldin İndeksi (DBI vs K)



Şekil 5. Silhouette Katsayısı (Silhouette vs K)



Şekil 6. K-Means Kümeleme (3B Görünüm)

4.2. K-Means Modelinin Uygulanması ve Küme Yapısı

Optimum küme sayısı k = 3 olarak belirlendikten sonra, K-Means modeli ürünleri stok performanslarına göre üç grupta sınıflandırmıştır:

Overstock (Aşırı Stok): Yüksek stok düzeyine karşın düşük satış hacmine sahip ürünler,

Balanced (Dengeli Stok): Satış, stok ve sipariş miktarları arasında denge bulunan ürünler,

Understock (Yetersiz Stok): Düşük stok miktarına rağmen yüksek talep veya satış hacmi gösteren ürünler.

Şekil 1, Inventory Level (Envanter Seviyesi) ile Units Sold (Satılan Birimler) arasındaki dağılımı göstermektedir.

Mavi bölge, stok fazlası bulunan ancak satış hacmi düşük ürünleri (Overstock),

Turuncu bölge, satış ve stok düzeyinin dengede olduğu ürünleri (Balanced),

Yeşil bölge ise stok seviyesi düşük fakat satış talebi yüksek ürünleri (Understock) temsil etmektedir.

Üç boyutlu görselleştirme (Şekil 6), Inventory Level, Units Sold ve Units Ordered değişkenlerinin birlikte değerlendirilmesiyle kümelerin uzaydaki ayrımını açık biçimde göstermektedir. Bu görsel analiz, K-Means algoritmasının stok yönetimi bağlamında ürünleri nicel özelliklerine göre anlamlı biçimde gruplandırabildiğini doğrulamaktadır.

4.3. Model Performansı ve Değerlendirme

Analiz sonuçlarına göre, k = 3 değeri, tüm metrikler açısından model için en uygun küme sayısıdır.

Modelin temel performans ölçütleri aşağıdaki gibi hesaplanmıştır:

Tablo 1: Performans Ölçüt Sonuçları

Performans Ölçütü	**Değer**	**Açıklama**
Inertia (WSS)	101.751,79	Kümelerin kompaktlığının yeterli düzeyde olduğunu göstermektedir.
Silhouette Katsayısı	0,3141	Kümeler arası ayrımın makul ve dengeli olduğunu ifade etmektedir.
Davies–Bouldin İndeksi (DBI)	Düşük	Kümeler arası ayrımın güçlü olduğunu göstermektedir.
Calinski–Harabasz Skoru (CH)	Yüksek	Kümelerin iyi ayrıştığını ve içsel homojenliğin yüksek olduğunu ortaya koymaktadır.

Bu metrikler bir arada değerlendirildiğinde, K-Means modelinin stok verilerini doğru, dengeli ve anlamlı biçimde sınıflandırabildiği sonucuna ulaşılmıştır.

4.4. Bulguların Yorumlanması

Elde edilen kümeleme sonuçları, veriye dayalı karar destek sistemlerinin envanter yönetiminde sağladığı avantajları açık biçimde ortaya koymaktadır.

Özellikle Balanced (dengeli stok) kümesinde yer alan ürünler, sipariş yenileme politikalarının ve stok optimizasyon stratejilerinin belirlenmesinde referans olarak kullanılabilecek bir temel sunmaktadır.

Buna karşın, Overstock (aşırı stok) grubundaki ürünler, gereksiz sermaye bağlanması, depolama maliyetlerinin artması ve stok devir hızının azalması gibi olumsuzluklara neden olmaktadır.

Understock (yetersiz stok) grubunda ise satış fırsatlarının kaçırılması, müşteri memnuniyetsizliği ve tedarik zinciri aksaklıkları riski öne çıkmaktadır.

Dolayısıyla, bu analiz, işletmelere stok dengesini sürdürülebilir biçimde yönetebilmeleri için güçlü, veri destekli bir karar verme çerçevesi sunmaktadır.

K-Means algoritması, yalnızca geçmiş stok davranışlarını analiz eden bir araç değil; aynı zamanda geleceğe dönük talep planlaması, stok optimizasyonu ve operasyonel verimlilik stratejilerinin geliştirilmesine katkı sağlayan etkin bir karar destek aracıdır.

5. TARTIŞMA VE SONUÇ

Bu çalışma, perakende tedarik zincirlerinde stok yönetiminin iyileştirilmesi amacıyla veri odaklı bir karar destek yaklaşımı geliştirmeyi hedeflemiştir. K-Means kümeleme algoritması kullanılarak gerçekleştirilen analiz sonucunda, ürünlerin satış performansı, envanter seviyesi ve sipariş sıklığına dayalı olarak üç temel stok grubu (Aşırı Stok, Dengeli Stok, Yetersiz Stok) tanımlanmıştır. Bu sınıflandırma, işletmelerin stok politikalarını nesnel verilere dayalı biçimde gözden geçirebilmeleri için uygulanabilir bir yöntem sunmaktadır.

5.1. Bulguların Tartışılması

Analiz bulguları, stok dengesinin korunması ve operasyonel verimliliğin artırılması açısından veri temelli yaklaşımların önemini ortaya koymuştur.

Kümeleme sonuçlarına göre:

Balanced (Dengeli Stok) kümesinde yer alan ürünler, stok düzeyi ile satış talebi arasında uyumlu bir ilişki sergileyerek işletmenin hedeflediği ideal stok yapısını temsil etmektedir.

Overstock (Aşırı Stok) kümesindeki ürünler, yüksek stok miktarına rağmen düşük satış hacmi göstermekte; bu durum işletme sermayesinin verimsiz kullanımına ve depolama maliyetlerinin artmasına yol açmaktadır.

Understock (Yetersiz Stok) kümesinde yer alan ürünlerde ise talebin stok miktarını aşması nedeniyle satış kayıpları yaşanmakta, müşteri memnuniyeti olumsuz etkilenmektedir.

Bu sonuçlar, literatürdeki benzer çalışmalarla (ör. Lolli et al., 2014; Khanorkar & Kane, 2023; Naznin et al., 2024) uyumluluk göstermektedir. Özellikle çok kriterli karar verme ve veri madenciliği temelli yaklaşımların stok dengesizliğini azaltmada etkili olduğu bulgusu, bu çalışmada da doğrulanmıştır.

Ayrıca, kullanılan K-Means algoritmasının yüksek sayıda ürün verisini hızlı biçimde sınıflandırabilmesi, yöntemin küçük ve orta ölçekli işletmeler (KOBİ) için uygulanabilirliğini artırmaktadır. Modelin düşük hesaplama maliyeti ve yüksek yorumlanabilirliği, karar vericilere dijital dönüşüm sürecine entegre edilebilecek bir analitik araç kazandırmaktadır.

5.2. Sonuçlar ve Katkılar

Bu araştırmanın temel katkısı, perakende sektöründe stok optimizasyonuna yönelik basit, açıklanabilir ve veri destekli bir kümeleme yaklaşımı önermesidir.

Elde edilen sonuçlar şu şekilde özetlenebilir:

K-Means algoritması, satış, stok ve sipariş verilerini birlikte değerlendirerek stok kalemlerini anlamlı biçimde sınıflandırmıştır.

k = 3 değeri, tüm istatistiksel ölçütlere göre optimum küme sayısı olarak belirlenmiş ve modelin güvenilirliği doğrulanmıştır.

Kümeleme sonucu elde edilen stok profilleri, envanter dengesinin korunması, sipariş yenileme politikalarının planlanması ve maliyet azaltımı açısından işletmelere güçlü bir karar desteği sunmaktadır.

Çalışma, veri madenciliği temelli karar destek sistemlerinin, özellikle KOBİ'lerde dijitalleşme ve verimlilik artışı sağlamada etkin biçimde kullanılabileceğini göstermektedir.

Bu çalışma perakende tedarik zincirlerinde stok yönetiminin veri temelli bir yaklaşımla yeniden yapılandırılabileceğini göstermektedir. K-Means kümeleme yöntemi, stok kalemlerini davranışsal benzerliklerine göre sınıflandırarak, yöneticilere ölçülebilir, yorumlanabilir ve uygulanabilir bir karar desteği sunmaktadır. Bu sayede işletmeler, aşırı stok ve yetersiz stok risklerini azaltarak kaynaklarını daha verimli kullanabilir, müşteri memnuniyetini artırabilir ve sürdürülebilir rekabet avantajı elde edebilir.

5.3. Kısıtlar ve Gelecek Çalışmalar

Bu araştırmanın temel kısıtı, analizde kullanılan veri setinin sınırlı bir zaman dilimini temsil etmesidir. Gelecekte yapılacak çalışmalarda:

Daha uzun dönemli veya farklı sektörlerden veri kümeleri üzerinde modelin test edilmesi,

K-Means dışındaki diğer kümeleme algoritmalarının (ör. DBSCAN, Gaussian Mixture Models) karşılaştırmalı olarak uygulanması,

Zaman serisi temelli tahminleme modelleriyle (ARIMA, LSTM, Prophet) entegrasyon sağlanması önerilmektedir.

Ayrıca, stok sınıflandırmasının işletme performansına etkisini ölçmek üzere çok kriterli karar verme (AHP, TOPSIS) veya makine öğrenmesi temelli optimizasyon yaklaşımlarının eklenmesi, yöntemin pratik kullanım değerini artıracaktır.

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ÖZET

Bu çalışma, mühendislik ahşap malzemelerinin ekonomik yönünü çok boyutlu bir çerçevede incelemeyi amaçlamaktadır. Malzeme tercihlerinde yalnızca ilk maliyetlerin değil, tüm yaşam döngüsü boyunca ortaya çıkan giderlerin değerlendirilmesi gerektiği göz önünde bulundurularak; LVL, CLT, OSB, Yonga levha/MDF ve Glulam gibi ürünlerin hammadde maliyeti, üretim enerjisi, işçilik gereksinimi, nakliye maliyeti, bakım ihtiyacı ve uzun vadeli performans maliyetleri kapsamlı şekilde analiz edilmiştir. Araştırma sonuçları, mühendislik ahşaplarının birçok durumda çelik ve beton gibi geleneksel malzemelerden daha düşük toplam maliyet sunduğunu göstermektedir. Özellikle CLT ve Glulam gibi yüksek taşıyıcı performansa sahip malzemelerin prefabrik üretime uygun olmaları, montaj sürelerini büyük ölçüde kısaltarak işçilik maliyetlerini azaltmaktadır. LVL' nin uzun açıklıklı yapılarda sunduğu yüksek performans, temel ve bağlantı elemanlarında maliyet avantajları yaratmaktadır. OSB ve MDF' nin ise düşük üretim maliyetleri sayesinde iç mekân uygulamalarında ekonomik çözümler sunduğu belirlenmiştir. Ayrıca mühendislik ahşapları, hafiflikleri nedeniyle nakliye maliyetlerini azaltmakta ve enerji verimliliği sayesinde yapıların işletme giderlerini düşürmektedir. Çalışmada yaşam döngüsü maliyeti analizleri de ele alınmış ve ahşap malzemelerin karbon depolama kapasitesi sayesinde çevresel sürdürülebilirlik ve ekonomik değer kazandırdığı ortaya konmuştur. Genel olarak mühendislik ahşaplarının ilk yatırım maliyetinin genellikle orta düzeyde olmasına rağmen, işletme ve bakım maliyetlerinin düşük olması nedeniyle uzun vadede ekonomik açıdan oldukça avantajlı olduğu sonucuna ulaşılmıştır.

Anahtar Kelimeler: Mühendislik Ahşabı, Maliyet analizi, CLT, LVL, Glulam, Sürdürülebilir Ekonomi

ECONOMIC ASSESSMENT AND COST ANALYSIS OF ENGINEERED WOOD PRODUCTS

ABSTRACT

This study presents an extensive economic evaluation of engineered wood products by examining both short-term and long-term cost parameters that influence material selection in contemporary construction. The analysis considers major engineered wood products—including LVL, CLT, OSB, Particleboard/MDF, and Glulam—and assesses them based on raw material costs, energy consumption during manufacturing, labor requirements, transportation expenses, maintenance needs, and overall lifecycle cost performance. The findings reveal that engineered wood often provides more cost-effective solutions than traditional materials such as concrete and steel, particularly when viewed through a lifecycle assessment framework. CLT and Glulam offer substantial economic advantages due to their compatibility with prefabrication, significantly reducing on-site labor and construction duration. LVL provides cost savings in long-span applications where steel members are traditionally used. OSB and MDF contribute to cost reduction in interior finishes and non-structural applications because of their low production costs and efficient use of wood residues. Furthermore, the lightweight nature of engineered wood products reduces transportation expenses and foundation requirements. The study also incorporates a sustainability-based economic perspective, emphasizing the role of engineered wood in carbon storage, waste reduction, and energy efficiency. These attributes translate into long-term operational savings and potential economic incentives such as carbon credits. Overall, the results indicate that although some engineered wood systems may have moderate initial costs, their reduced maintenance demands, rapid installation, and high energy performance make them financially advantageous over the building's lifecycle. Consequently, engineered wood products represent a strategically valuable option for cost-efficient and environmentally sustainable construction.

Keywords: Engineered Wood, Cost Analysis, CLT, LVL, Glulam, Sustainable Economy

1. GİRİŞ

Son yıllarda yapı sektöründe hem ekonomik hem ekolojik baskılar artmış, bu durum maliyet verimliliği yüksek ve sürdürülebilir malzemelere olan talebi hızla yükseltmiştir. Geleneksel inşaat malzemeleri olan çelik ve beton, yüksek üretim enerjisi gerektirmeleri, karbon salım oranlarının yüksek oluşu ve işçilik-montaj maliyetlerinin giderek artması nedeniyle alternatif arayışlarını tetiklemiştir (Pei et al., 2020). Bu noktada mühendislik ahşabı, yalnızca çevreci bir çözüm olarak değil, aynı zamanda ekonomik açıdan rekabetçi bir yapı malzemesi olarak ön plana çıkmaktadır.

Mühendislik ahşap malzemelerinin ekonomik değerini belirleyen temel faktörler şunlardır:

- Ham madde maliyeti
- Üretim yöntemleri ve enerji tüketimi
- İşçilik yoğunluğu
- Prefabrikasyon imkânı
- Nakliye maliyetleri
- Uzun ömür ve bakım gereksinimleri
- Geri dönüştürüle bilirlik ve karbon kredileri

Bu çalışma, mühendislik ahşaplarının ekonomik yönünü bütüncül bir bakış ile değerlendirmekte, her ürünün kısa ve uzun vadeli maliyet profilini karşılaştırmalı şekilde incelemektedir.

2. EKONOMİK ANALİZDE KULLANILAN TEMEL KRİTERLER

Maliyet değerlendirmesi yalnızca ürün fiyatını değil, tüm yaşam döngüsünü kapsamalıdır. Bu nedenle, çalışmada aşağıdaki ekonomik bileşenler dikkate alınmıştır:

2.1 Ham Madde Maliyeti

LVL, CLT ve Glulam genellikle çam, ladin gibi hızlı büyüyen türlerden elde edildiği için hammadde temini göreceli olarak ekonomiktir. OSB, MDF ve yonga levha gibi levhalar ise düşük kaliteli odun, odun atığı ve endüstriyel artıklarla üretildiğinden hammadde maliyeti en düşük grubu oluşturur.

2.2 Üretim Enerjisi ve Teknolojisi

- Beton → yüksek enerji, yüksek karbon salımı
- Çelik → çok yüksek enerji ve maliyet
- CLT, LVL, Glulam → orta düzey enerji
- OSB / MDF → düşük enerji gereksinimi

Ahşap, üretim sırasında enerji verimliliği sağladığı için ekonomik açıdan avantajlıdır (Brandner et al., 2016).

2.3 İşçilik ve Montaj Maliyetleri

Prefabrikasyon sayesinde mühendislik ahşap ürünleri, sahada daha az işçilik gerektirir. CLT paneller ise birkaç gün içerisinde çok katlı bir yapının montajını mümkün kılar.

2.4 Nakliye Maliyetleri

Ahşap malzemeler beton ve çeliğe göre çok daha hafiftir. Hafiflik → düşük yakıt tüketimi → düşük lojistik maliyeti.

2.5 Uzun Vadeli Bakım ve Onarım

Koruyucu işlemlerle mühendislik ahşabı uzun ömürlüdür. Ek olarak:

- Beton → çatlak onarımı
- Çelik → korozyon bakımı
- Ahşap → düzenli fakat düşük maliyetli bakım

2.6 Yapının Ömrü ve Artık Değer

Mühendislik ahşabı:

- Geri dönüştürülebilir,
- Yeniden yapı bileşeni olarak kullanılabilir,
- Karbon sertifikası gelirleri oluşturabilir.

3. MÜHENDISLIK AHŞAP TÜRLERININ EKONOMIK ANALIZI

3.1 LVL'nin Ekonomik Değerlendirmesi

LVL, uzun lif yönünde yüksek dayanım sunduğu için taşıyıcı elemanlarda çeliğe alternatif olarak kullanılabilir. Üretimi enerji açısından verimli olup yüksek boyut kararlılığı sağlar. Uzun açıklıkların betonarme yapılara göre daha düşük işçilik maliyetiyle geçilebilmesi ekonomik avantaj yaratır. Ayrıca prefabrik yapı sektöründe LVL, montaj süresini kısaltarak toplam proje süresini önemli ölçüde azaltır.

3.2 CLT' nin Ekonomik Değerlendirmesi

CLT özellikle çok katlı konutlarda çeliğe ekonomik alternatif hâline gelmiştir. Paneller fabrika ortamında hazırlanır ve sahada sadece birleştirme işlemleri yapılır. Bu, hem işçilik hem zaman maliyetini düşürür. CLT yapılar, betonarme yapılara kıyasla daha hafif olduğu için temel maliyetleri de ciddi miktarda azalır. Enerji verimliliği yüksek olduğu için işletme maliyetlerini düşürür.

3.3 OSB'nin Ekonomik Değerlendirmesi

OSB düşük maliyetlidir; küçük çaplı kerestelerden ve endüstri atıklarından üretildiği için ham madde fiyatı çok ekonomiktir. Genellikle taşıyıcı olmayan bölümlerde kullanıldığından ürün fiyatı bakımından en uygun çözümlerden biridir. Hafif yapısı nedeniyle nakliye maliyeti düşüktür.

3.4 Particleboard / MDF'nin Ekonomik Değeri

Mobilya ve iç mekân uygulamalarında yüksek fiyat-performans dengesi sunar. Yapısal amaçla kullanılmasa da iç mekân kaplamalarında ekonomik avantaj sağlar. Üretimde geri dönüşümlü malzemelerin kullanılabilmesi hem maliyeti düşürür hem de sürdürülebilirliği artırır.

3.5 Glulam'ın Ekonomik Değerlendirmesi

Glulam yüksek taşıyıcı kapasiteye sahip olması ve uzun açıklıklı kirişlerde çeliğe ekonomik alternatif oluşturmasıyla öne çıkar. Özel şekilli kavisli elemanların üretilebilmesi sayesinde mimari maliyetleri düşürür. İşçilik gereksinimi düşüktür ve üretimi rasyonel enerji tüketir. Ayrıca bakım maliyetleri çeliğe göre daha düşüktür.

4. YAŞAM DÖNGÜSÜ MALIYETI (LCC) AÇISINDAN KARŞILAŞTIRMA

Yaşam döngüsü maliyeti, bir malzemenin:

- Üretim,
- Nakliye,
- Montaj,
- İşletme,
- Bakım,
- Söküm ve yeniden kullanım

gibi tüm aşamalarının parasal değeridir. Sonuç olarak;

- Beton → İlk maliyet düşük, uzun vadeli bakım ve enerji kaybı yüksek.
- Çelik → İlk maliyet yüksek, bakım maliyeti yüksek.
- Ahşap → İlk maliyeti orta, bakım maliyeti düşük, işletme maliyeti düşük.

Araştırmalar, CLT binaların ömür boyu maliyetinin betonarme binalara göre **%10–25** daha düşük olabileceğini göstermektedir (Espinoza et al., 2019).

5. SÜRDÜRÜLEBILIRLIK VE EKOLOJIK EKONOMI

Mühendislik ahşabı ekonomik değerlendirmenin yanında çevresel ekonomide de önemli bir rol oynar.

5.1 Karbon Depolama

1 m³ ahşap yaklaşık **1 ton CO_2** depolar. Bu, karbon kredisi potansiyeli anlamına gelir → maliyet avantajı.

5.2 Enerji Tasarrufu

Ahşap yapılarda ısı yalıtımı yüksek olduğu için işletme maliyetleri düşüktür.

5.3 Atık Yönetimi

Çelik ve betonun tersine:

- Ahşap artıklar tekrar değerlendirilebilir,
- OSB/MDF üretiminde endüstri atıkları kullanılır,
- Malzemenin çevresel maliyeti düşüktür.

Bu faktörler ekonomik sürdürülebilirlik açısından mühendislik ahşaplarını avantajlı hâle getirir.

6. GENEL MALIYET KARŞILAŞTIRMASI: ÜRÜNLERE GÖRE EKONOMIK PROFIL

Aşağıda ürünlerin özet ekonomik profili yer almaktadır:

Tablo 6.1. Ahşap Malzeme Türlerinin Karşılaştırılması

MALZEME	BAŞLANGIÇ MALİYET	İŞCİLİK MALİYETİ	NAKLİYE	BAKIM	UZUN VADELİ EKONOMİ
LVL	ORTA	DÜŞÜK	DÜŞÜK	DÜŞÜK	YÜKSEK VERİM
CLT	ORTA-YÜKSEK	ÇOK DÜŞÜK	DÜŞÜK	DÜŞÜK	EN EKONOMİK LCC
OSB	ÇOK DÜŞÜK	DÜŞÜK	DÜŞÜK	ORTA	İÇ MEKÂNDA EKONOMİK
MDF/PB	DÜŞÜK	DÜŞÜK	DÜŞÜK	ORTA	MOBİLYA İÇİN UYGUN
GLULAM	ORTA	DÜŞÜK	DÜŞÜK	DÜŞÜK	ÇELİĞE EKONOMİK ALTERNATİF

7. SONUÇ

Bu çalışma, mühendislik ahşap malzemelerinin ekonomik değerini kapsamlı şekilde analiz etmiş ve her ürünün kısa ve uzun vadeli maliyet profilini ortaya koymuştur. Çalışmanın bulgularına göre:

- **CLT** çok katlı yapılarda betonarmeye göre daha düşük toplam maliyet sunmaktadır.
- **LVL** ve **Glulam**, çeliğe kıyasla daha ekonomik taşıyıcı seçeneklerdir.
- **OSB** ve **MDF**, iç mekân ve kaplama işlerinde düşük maliyetli çözümler oluşturur.
- Prefabrik üretim, montaj süresini kısaltarak toplam proje maliyetini belirgin düzeyde düşürür.
- Karbon depolama ve düşük enerji tüketimi sayesinde mühendislik ahşabı, sadece ekonomik değil, çevresel açıdan da önemli avantajlar sunmaktadır.

Sonuç olarak, mühendislik ahşapları hem ekonomik hem ekolojik sürdürülebilirlik açısından giderek daha cazip bir yapı malzemesi hâline gelmektedir. Gelecekte, karbon nötr inşa tekniklerinin yaygınlaşmasıyla bu malzemelerin kullanımının daha da artacağı öngörülmektedir.

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MÜHENDİSLİK AHŞAP MALZEMELERİN İNŞAAT ALANINDA KULLANIMI VE YAPISAL ÖZELLİKLERİ

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ÖZET

Bu çalışma, mühendislik ahşap malzemelerinin modern inşaat sektöründeki rolünü, bu malzemelerin yapısal performanslarını ve uygulama alanlarını kapsamlı biçimde incelemektedir. Doğal ahşabın fiziksel ve mekanik zayıflıklarını geliştirmek amacıyla üretilen mühendislik ahşapları, günümüzde sürdürülebilirlik, hafiflik, yüksek dayanım ve prefabrikasyon imkânı gibi avantajlarıyla geleneksel malzemelere alternatif oluşturmaktadır. Çalışmada ele alınan Laminated Veneer Lumber (LVL), Cross-Laminated Timber (CLT), Oriented Strand Board (OSB), Particleboard/MDF ve Glue Laminated Timber (Glulam) gibi ürünlerin üretim teknikleri, malzeme bileşimleri ve dayanım özellikleri ayrıntılı olarak açıklanmıştır. LVL ve Glulam gibi yüksek taşıma kapasitesine sahip ürünlerin özellikle kiriş ve kolonlarda çeliğe alternatif oluşturduğu; CLT'nin ise çok katlı yapılarda betonarme sistemlere benzer bir taşıyıcı performans sunduğu belirlenmiştir. OSB ve MDF gibi levha ürünleri ise iç mekân uygulamalarında, kaplamalarda ve duvar elemanlarında ekonomik ve pratik çözümler sağlamaktadır. Çalışma, mühendislik ahşaplarının boyutsal kararlılık, rijitlik, yangın davranışı, sismik dayanım ve çevresel performans açısından sahip olduğu avantajları geniş bir çerçevede değerlendirmektedir. Sonuç olarak, mühendislik ahşap malzemelerin inşaat sektöründe artan şekilde tercih edilmesinin nedeninin yalnızca yapısal faydaları değil, aynı zamanda sürdürülebilirlik ve düşük karbon odaklı tasarım ilkelerine uyum sağlama kapasitesi olduğu vurgulanmaktadır. Bu bulgular, mühendislik ahşaplarının geleceğin yapı teknolojilerinde önemli bir konumda olacağını göstermektedir.

Anahtar Kelimeler: Mühendislik Ahşap Malzemeleri, LVL, CLT, OSB, Glulam, Sürdürülebilir Yapı Malzemeleri

STRUCTURAL CHARACTERISTICS AND CONSTRUCTION APPLICATIONS OF ENGINEERED WOOD MATERIALS

ABSTRACT

This study provides a comprehensive examination of engineered wood materials and their application in the modern construction industry, focusing on their structural performance, physical behavior, and functional advantages. Engineered wood products—such as Laminated Veneer Lumber (LVL), Cross-Laminated Timber (CLT), Oriented Strand Board (OSB), Particleboard/MDF, and Glue Laminated Timber (Glulam)—have emerged as advanced alternatives to traditional building materials due to their enhanced strength, dimensional stability, and sustainability features. These materials are produced by reorganizing wood fibers, veneers, strands, or particles through controlled industrial processes, resulting in improved mechanical consistency and reduced defects compared to natural solid wood. The study discusses the manufacturing principles, structural properties, and functional capabilities of each engineered wood type. LVL and Glulam demonstrate high load-bearing capacity, making them suitable for beams, columns, and long-span structural elements, often replacing steel members. CLT functions as a mass timber panel system capable of serving as walls, floors, and multi-story load-bearing structures, offering high stiffness and excellent seismic performance. OSB and MDF, while not primarily used as structural components, are widely utilized in interior applications and sheathing due to their cost-efficiency and ease of processing. The article further highlights the fire performance, thermal behavior, and environmental contributions of engineered wood products. Their renewable nature, carbon storage capacity, and compatibility with sustainable design principles make them integral to low-carbon construction strategies. Ultimately, the study concludes that engineered wood materials represent an innovative, efficient, and environmentally responsible class of building materials poised to play an increasingly significant role in future construction technologies.

Keywords: Engineered wood materials, LVL, CLT, OSB, Glulam, Sustainable construction materials

1. GİRİŞ

Ahşap, insanlık tarihinin en eski yapı malzemelerinden biridir. Doğal yapısı, kolay işlenebilirliği ve yenilenebilir olması nedeniyle yüzyıllar boyunca hem geleneksel hem de modern mimaride önemli bir rol oynamıştır. Ancak son yüzyılda sanayileşmenin etkisiyle beton ve çelik gibi malzemelerin yaygınlaşması, ahşabın yapı sektöründeki kullanım oranını azaltmıştır. Bununla birlikte, son yıllarda artan çevre bilinci, karbon ayak izinin azaltılmasına yönelik politikalar ve sürdürülebilir malzeme arayışları, ahşabın yeniden popülerlik kazanmasına neden olmuştur (Yıldız & Akbaş, 2020).

Bu süreçte geliştirilen mühendislik ahşap malzemeleri, doğal ahşabın zayıf yönlerini (örneğin düzensiz lif yapısı, düşük dayanım ve boyutsal kararsızlık) ortadan kaldırarak üstün mekanik ve fiziksel özellikler sunmaktadır. Mühendislik ahşapları, ahşap liflerinin, kaplamaların veya parçacıkların endüstriyel yöntemlerle yeniden birleştirilmesiyle elde edilir. Bu yöntem, hem daha yüksek mukavemet hem de malzeme homojenliği sağlar (Blaß et al., 2019).

Bu çalışmada; Laminated Veneer Lumber (LVL), Cross-Laminated Timber (CLT), Oriented Strand Board (OSB), Particleboard / MDF ve Glue Laminated Timber (Glulam) olmak üzere beş temel mühendislik ahşap türü teknik açıdan incelenmiştir. Her bir malzemenin üretim yöntemi, dayanım karakteristiği, kullanım alanı ve çevresel performansı değerlendirilmiş; ayrıca bu malzemelerin yapı sektörüne sunduğu yenilikçi katkılar tartışılmıştır.

Mühendislik ahşap ürünlerinin incelenmesi, yalnızca malzeme bilimi açısından değil, aynı zamanda sürdürülebilir mimari ve yeşil bina uygulamaları açısından da önemlidir. Zira bu malzemeler, karbon salımını azaltmakta, enerji verimliliğini artırmakta ve döngüsel ekonomiye katkı sağlamaktadır.

2. MÜHENDİSLİK AHŞAP MALZEMELERİN TÜRLERİ VE ÖZELLİKLERİ

2.1 Laminated Veneer Lumber (LVL)

Laminated Veneer Lumber (LVL), ince ahşap kaplamaların lif yönü boyunca fenol-formaldehit gibi reçinelerle yapıştırılması sonucu elde edilen yüksek mukavemetli bir mühendislik ahşap türüdür. LVL üretiminde genellikle çam, ladin veya kavak gibi hızlı büyüyen ağaç türleri tercih edilir. Bu malzeme, lif yönünde yüksek dayanım göstermesi sayesinde özellikle kiriş, kolon, çatı ve döşeme gibi taşıyıcı elemanlarda kullanılmaktadır (Barber, 2021).

LVL'in homojen yapısı, doğal ahşapta görülen lif düzensizliklerini ortadan kaldırarak öngörülebilir mekanik performans sağlar. Ayrıca, büyük boyutlu elemanların üretimine olanak tanıdığı için uzun açıklıklı yapılar için uygun bir alternatiftir. Yüksek yoğunluklu yapısı sayesinde eğilme, burkulma ve kesme dayanımları oldukça yüksektir (Kurt & Çolak, 2020).



Şekil 2.1.1. Çok Katmanlı Yapısıyla Lamine Kaplama Kereste (LVL) Kiriş ve Kolon Detayları.

2.2 Cross-Laminated Timber (CLT)

Cross-Laminated Timber (CLT), birbiriyle dik yönde yerleştirilmiş ahşap tabakaların preslenerek birbirine yapıştırılmasıyla üretilir. Katmanların çapraz yerleştirilmesi, malzemenin hem boyutsal kararlılığını hem de yük taşıma kapasitesini artırır. CLT paneller, özellikle duvar, döşeme ve çatı elemanlarında yaygın olarak kullanılmaktadır (Brandner et al., 2016).

CLT'nin en önemli avantajı, çok katlı ahşap yapıların inşa edilmesine olanak tanımasıdır. Prefabrik olarak üretilen panellerin montaj süresi kısa olup, inşaat sahasında işçilik maliyetini azaltır. Ayrıca CLT, yangına karşı dayanıklı yapısı ve enerji verimliliği ile sürdürülebilir yapı projelerinde sıkça tercih edilmektedir (Espinoza et al., 2019).



Şekil 2.2.1. Amasya İlinde İnşası Yapılan Otelde Dış Duvarların ve Döşemelerin CLT Malzemesi ile İmal Edilmesi. (Ulusal Ahşap Birliği, 2020.)

2.3 Oriented Strand Board (OSB)

OSB, belirli yönlerde hizalanmış ince odun yongalarının suya dayanıklı reçinelerle preslenmesiyle oluşturulan levha tipi bir mühendislik ahşap malzemedir. OSB paneller, lif yönü kontrollü şekilde düzenlendiği için geleneksel kontrplaklara kıyasla daha yüksek rijitlik ve boyutsal kararlılık sunar (Rammer & Zelinka, 2020).

OSB, zemin alt yapısı, duvar kaplaması, çatı döşemesi ve taşıyıcı yüzeylerde kullanılmaktadır. Ayrıca düşük maliyetli, dayanıklı ve kolay işlenebilir yapısı nedeniyle hem konut hem endüstriyel yapılarda tercih edilir. OSB'nin üretiminde küçük çaplı ağaçların ve yan ürünlerin kullanılması, kaynak verimliliğini artıran önemli bir sürdürülebilirlik avantajı sağlar.



Şekil 2.3.1. Çift Taraflı OSB Üzerine Yapılan Alçıpan Kaplama Çalışması

2.4 Particleboard / MDF

Particleboard ve MDF (Medium Density Fiberboard), ahşap talaşı veya liflerin sentetik reçinelerle birleştirilip yüksek basınç altında sıkıştırılmasıyla üretilen malzemelerdir. Bu malzemeler, homojen yüzeyleri ve düzgün dokuları sayesinde özellikle iç mekân uygulamalarında tercih edilir (Çolak & Erdinler, 2018).

Yapısal dayanımı sınırlı olmasına karşın, işlenebilirlik ve yüzey kalitesi açısından önemli avantajlar sunar. Dolap, raf, duvar paneli ve mobilya üretiminde yaygın olarak kullanılır. Üretim sürecinde geri dönüştürülmüş ahşap atıklarının kullanılabilmesi, çevresel açıdan önemli bir kazanımdır.



Şekil 2.4.1. Mutfak Mobilyası İmalatında Kullanılan MDF Gövde ve Raf Sistemi Uygulaması.

2.5 Glue Laminated Timber (Glulam)

Glulam, ince ahşap lamellerin birbirine paralel şekilde yapıştırılmasıyla elde edilen yüksek dayanımlı bir yapı malzemesidir. Genellikle taşıyıcı kiriş, kolon, kemer ve köprü elemanlarında kullanılır. Lamellerin seçici şekilde birleştirilmesi, hem malzeme israfını azaltır hem de yüksek mekanik performans sağlar (Forest Products Laboratory, 2010).

Glulam'ın en önemli avantajlarından biri, büyük açıklıkları geçebilme kapasitesidir. Aynı zamanda doğal ahşap görünümünü koruyarak estetik bir görünüm sunar. Yangın dayanımı açısından da güvenli bir malzeme olarak kabul edilir; çünkü yüzeydeki karbonlaşma tabakası iç katmanları koruyarak mukavemetin düşmesini geciktirir.

3. MÜHENDİSLİK AHŞAP MALZEMELERİN İNŞAATTA KULLANIMI

Mühendislik ahşap malzemeler, modern inşaat uygulamalarında taşıyıcı sistemlerden kaplama elemanlarına kadar geniş bir kullanım yelpazesi sunar. LVL ve Glulam, özellikle çatı kirişleri, kolonlar ve köprü elemanlarında tercih edilirken; CLT, çok katlı yapıların duvar ve döşeme sistemlerinde kullanılır. OSB ve MDF ise genellikle zemin kaplamaları, duvar panelleri ve iç mekân tasarımlarında görev alır (Harte, 2017).

Bu malzemelerin tercih edilmesinde sadece dayanım değil, aynı zamanda montaj kolaylığı, hafiflik ve prefabrikasyona uygunluk gibi özellikler de etkilidir. Örneğin, CLT panelleri fabrika ortamında hazırlanıp sahaya taşındığında montaj süresi önemli ölçüde kısalır. LVL ve Glulam gibi yüksek dayanımlı malzemeler ise çelik ve betona alternatif taşıyıcı çözümler sunarak karbon ayak izini azaltır.

4. YAPISAL PERFORMANS, SÜRDÜRÜLEBİLİRLİK VE UYGULAMA BOYUTLARI

Mühendislik ahşap ürünlerinin yapısal performansı, kullanılan ahşap türü, reçine kalitesi ve üretim yöntemi ile doğrudan ilişkilidir. LVL ve Glulam, uzun ömürlü ve yüksek dayanımlı taşıyıcı sistemlerde kullanılırken; CLT paneller, hem yatay hem dikey yükleri güvenle taşıyabilme özelliğine sahiptir. OSB ve MDF ise taşıyıcı özellikten ziyade tamamlayıcı görevler üstlenir.

Bu malzemelerin en önemli katkılarından biri de sürdürülebilirliktir. Yenilenebilir kaynaklardan üretildikleri için karbon depolama kapasitesine sahiptirler. Ayrıca, prefabrik üretim süreçleri sayesinde atık miktarı azalır, enerji verimliliği artar (Pei et al., 2020). Üstelik mühendislik ahşap malzemelerin geri dönüştürülebilir olması, döngüsel ekonomiye katkı sunmaktadır.

Mühendislik ahşaplarının hafif yapısı, nakliye ve montaj sırasında enerji tasarrufu sağlar. Yangın dayanımı, ses yalıtımı ve ısı performansı açısından da modern yönetmeliklerle uyumlu hale getirilmiştir. Bu yönüyle, mühendislik ahşapları hem çevresel hem teknik açıdan sürdürülebilir yapı sistemleri için güçlü bir alternatiftir.

5. SONUÇ VE DEĞERLENDİRME

Bu çalışma, mühendislik ahşap malzemelerin üretim teknikleri, yapısal özellikleri ve inşaat sektöründeki kullanım alanlarını kapsamlı biçimde değerlendirmiştir. Elde edilen sonuçlar göstermektedir ki, LVL, CLT ve Glulam gibi yüksek dayanımlı mühendislik ahşap türleri, taşıyıcı sistemlerde güvenle kullanılabilecek düzeyde performans sergilemektedir. OSB, MDF ve Particleboard ise yapısal olmayan alanlarda estetik ve işlevsel katkı sağlamaktadır.

Mühendislik ahşap ürünleri, yenilenebilir kaynaklardan üretildikleri için çevresel sürdürülebilirlik açısından büyük önem taşır. Hafiflik, enerji verimliliği ve karbon depolama özellikleri sayesinde geleceğin çevre dostu yapı teknolojilerinde önemli bir rol üstleneceklerdir. Sonuç olarak, bu malzemelerin inşaat sektöründeki etkin kullanımının artması, yalnızca teknik performansı değil, aynı zamanda ekolojik dengeyi de olumlu yönde etkileyecektir.

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YOLOV8n KULLANILARAK SALATALIĞIN (CUCUMIS SATIVUS L.) UZUNLUK VE AĞIRLIK ÖLÇÜMLERİNDE BİLGİSAYAR TABANLI YAKLAŞIM

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ÖZET

Tarımsal üretimde kalite sınıflandırması, verim yönetimi ve hasat zamanlamasının optimize edilmesi için meyve-sebze boyutlarının doğrulukla belirlenmesi büyük önem taşır. Bu nedenle boyut ölçümünün hızlı, temassız ve güvenilir biçimde yapılması günümüzde giderek zorunlu hale gelmektedir. Salatalık (Cucumis sativus L.) gibi ince ve eğrisel morfolojiye sahip ürünlerde yapılan manuel ölçüm işlemleri zaman kaybına neden olmakta ve hataya açık bir süreç oluşturmaktadır. Çalışmada, tek bir RGB kamera kullanarak gerçek zamanlı uzunluk ve ağırlık tahmini yapabilen, derin öğrenme tabanlı ve düşük maliyetli bir sistem geliştirilmiştir. Nesne tespiti için hız, doğruluk ve donanım verimliliği arasında optimum denge sağlayan YOLOv8n mimarisi kullanılmıştır. YOLOv8n'nin anchor-free yapısı, çok ölçekli özellik birleştirme yeteneği ve parçalı tahmin başlığı, salatalığın farklı aydınlatma, örtüşme ve şekil varyasyonlarında yüksek algılama duyarlılığı sağlamıştır. Toplam 999 görüntüden oluşan veri seti ile model eğitilmiş, tespit edilen meyvelerin piksel boyutları kamera kalibrasyonu yardımıyla santimetre cinsine dönüştürülmüş ve silindirik hacim modeli ile kütle değerleri tahmin edilmiştir. Sistemin kararlılığı, Bland–Altman uyum analizi ve ablation çalışmaları ile istatistiksel olarak doğrulanmıştır. Uzunluk ölçümleri için ortalama fark +0,40 cm (SD: 0,35 cm), ağırlık tahmini için −2,35 g (SD: 3,10 g) elde edilmiş, yöntemler arasında %95 güven aralığında güçlü bir uyum saptanmıştır. En iyi performans gösteren ablation modeli $R^2 = 0,994$, RMSE = 2,76 g ve MAE = 1,95 g değerlerine ulaşarak yüksek tahmin doğruluğu sergilemiştir. YOLOv8n tabanlı sistem yalnızca salatalık için değil, kabak ve patlıcan gibi benzer morfolojiye sahip ürünlerde de otomatik boyutlandırma ve ağırlık tahmini için kullanılabilir. Bu durum, modelin farklı ürün türlerinde yüksek genelleme kapasitesine sahip olduğunu göstermektedir. Sistem, akıllı tarım teknolojilerinde kalite kontrol, otonom hasat ve karar destek süreçlerine uygulanabilirliği sayesinde, sürdürülebilir ve dijital tarımsal üretimin geliştirilmesine önemli katkı sunmaktadır.

Anahtar kelimeler: Salatalık, YOLOv8n, Uzunluk ve ağırlık tahmini, Bilgisayar tabanlı ölçüm ,Tarımsal otomasyon

COMPUTER-BASED APPROACH FOR MEASURING THE LENGTH AND WEİGHT OF CUCUMBERS (CUCUMIS SATIVUS L.) USING YOLOV8N

ABSTRACT

Accurate determination of fruit and vegetable sizes is essential for optimising quality classification, yield management, and harvest timing in agricultural production. Consequently, fast, contactless, and reliable size measurement is increasingly important. Manual measurement of products with thin and curved morphologies, such as cucumbers (Cucumis sativus L.), results in time loss and introduces errors. In this study, a low-cost, deep learning-based system capable of real-time length and weight estimation using a single RGB camera was developed. The YOLOv8n architecture, which offers an optimal balance of speed, accuracy, and hardware efficiency for object detection, was employed. YOLOv8n's anchor-free structure, multi-scale feature fusion capability, and segmented prediction header provided high detection sensitivity for cucumbers under varying lighting conditions, overlap, and shape variations. The model was trained on a dataset of 999 images. The pixel dimensions of the detected fruits were converted to centimetres using camera calibration, and mass values were estimated using a cylindrical volume model. The stability of the system was statistically validated using Bland–Altman agreement analysis and ablation studies. For length measurements, the mean difference was +0.40 cm (SD: 0.35 cm), and for weight estimation, −2.35 g (SD: 3.10 g), indicating strong agreement between methods within a 95% confidence interval. The best-performing ablation model achieved $R^2 = 0.994$, RMSE = 2.76 g, and MAE = 1.95 g, demonstrating high prediction accuracy. The YOLOv8n-based system can be used for automatic sizing and weight estimation not only for cucumbers but also for products with similar morphology, such as courgettes and aubergines. This demonstrates the model's high generalisation capacity across different product types. The system contributes significantly to the development of sustainable and digital agricultural production through its applicability in quality control, autonomous harvesting, and decision support processes in smart farming technologies.

Keywords:Cucumber, YOLOv8n, length and weight estimation, computer-based measurement, agricultural automation

1.Giriş

Tarımda verimlilik, kalite kontrolü, artan gıda telebi ve otomasyon gereksinimlerinin artışı meyve-sebze üretiminde fenotipik özelliklerin hızlı ve temassız olarak ölçülmesini zorunlu kılmaktadır.Özellikle seralarda ve tarlada ticari öneme sahip olan salatalık (Cucumis sativus L.), uzun, ince ve zaman zaman eğrisel bir morfolojiye sahiptir. Bu nedenle, uzunluk gibi boyutsal özellikler hem sınıflandırma ve ambalajlama stratejileri hem de hasat zamanlaması açısından karar vericiler için kritik bir rol oynamaktadır. Son yıllarda makine görüşü ve derin öğrenme tabanlı yaklaşımlar, meyve ve sebzelerin boyutlandırma ve derecelendirme süreçlerinde sahada uygulanabilir çözümler sunmaktadır. Bu çözümler, klasik mekanik ve manuel ölçüm tekniklerine kıyasla sistemlere daha fazla esneklik, hız ve ölçeklenebilirlik kazandırmıştır. Derin öğrenmenin en yaygın uygulama alanlarından biri, görüntü tanıma ve sınıflandırmadır. Hasat sırasındaki toplama sürecinde tespit edilen salatalıkların boyutları, klasik yöntemlere kıyasla daha yüksek doğruluk oranlarıyla ölçülebilmektedir. Özellikle konvolüsyonel sinir ağları, bitkilerin çeşitli boyutlarının doğru bir şekilde sınıflandırılması ve bu bilgilerin analiz edilmesi için sıklıkla kullanılmaktadır (Ökten ve Yüzgeç, 2022). Bu yöntemlerin uygulanabilirliği, özellikle büyük veri setlerinde, özellik çıkarımı ve model eğitimi aşamalarındaki gelişmelerle doğrudan ilişkilidir (Akdere ve ark., 2023).Özellikle, derin öğrenme süreçlerinde kullanılan veri ön işleme ve model geliştirme teknikleri, salatalıkların boyutunu algılayacak sistemlerin etkinliğini artırmaktadır Makine öğrenmesi ve derin öğrenme algoritmalarındaki bu yenilikler, tarımda akıllı sistemlerin entegrasyonunu hızlandırmakta ve işleme, analiz ve karar verme süreçlerini optimize etmektedir (Erol ve İnkaya, 2023). Bununla birlikte, derin öğrenme uygulamalarının daha sağlıklı ve güvenilir sonuçlar verebilmesi için, uygun eğitim veri setlerinin ve model parametrelerinin belirlenmesi büyük önem taşımaktadır (Demiryege ve Ulukavak, 2022).Bu nedenle görüntü tabanlı otomatik boyut tahmini, tarımsal süreçlerin dijitalleştirilmesi ve maliyet-etkin uygulanabilirliği açısından önemli bir araştırma alanıdır (Neupane ve ark.,2023). Özellikle görüntü işleme tekniklerinin kullanımı, bitkilerin büyüme aşamalarının ve boyutlarının belirlenmesinde etkili bir yöntem sunmaktadır (Yaman ve Tuncer, 2022). Bu eğilim; tarlada ve serada karmaşık arka plan, değişken aydınlatma, kısmi örtüşme ve şekil eğriliği gibi zorlu koşullarda dahi tespit–segmentasyon–boyut çıkarımı zincirini baştan sona öğrenebilen uçtan uca modellerin yaygınlaşmasıyla hız kazanmıştır (Miranda ve ark.,2023) . Endüstriyel üretim hatlarında kütle veya boyut tahmini amacıyla geliştirilen makine görüşü ve derin öğrenme tabanlı entegre sistemler başarılı sonuçlar vermiştir. Bu tür yaklaşımlar, uzunluk ve çap gibi morfolojik öznitelikleri kütle ile ilişkilendirerek bu parametrelerin doğrudan ya da dolaylı biçimde ölçülebilir hale gelmesini sağlamaktadır (Liu ve ark.,2024). Benzer biçimde, tarımsal araştırmalarda da bu tür derin öğrenme tabanlı görsel sistemler, meyve ve sebzelerin boyut, kütle ve olgunluk düzeylerinin temassız biçimde tahmin edilmesinde önemli bir potansiyel ortaya koymaktadır. Salatalık (Cucumis sativus L.) , meyvenin eksenel eğriliği, yaprak-gövde ile renk/tekstür benzerliği, perspektif ve ölçek değişimleri, tek görüntüden güvenilir uzunluk kestirimini güçleştirir. Yapılan araştırmalarda, meyve boyutlandırma amacıyla stereo veya derinlik sensörleri, çok-görüşlü sistemler ve referans ölçekleyiciler kullanılmıştır. Bununla birlikte, yalnızca RGB görüntülerle çalışan derin öğrenme tabanlı modellerin de başarılı sonuçlar elde ettiği gösterilmiştir. Uzunluk tahmininde öne çıkan üç temel metodolojik kategori; tespit tabanlı (Faster/Mask R-CNN, YOLO ailesi), segmentasyon tabanlı ve anahtar nokta tabanlı ölçüm yaklaşımlarıdır (Mirbod ve ark,2023).CucumberAI gibi araçlar; kontur tabanlı meyve segmentasyonu, şekil sınıflaması ve (çeşitler arası) biçimsel farkların otomatik ayrımında doğruluk sağlamıştır.Uzunluk/çap ölçümlerine temel teşkil etmiştir (Xue ve ark.,2024).Boğum (node) tespiti, boğum arası mesafe ve gövde geometri hesapları; 2D görüntüler ve 3D nokta bulutu (PointNet++ tabanlı) yöntemlerle başarıyla yapılmıştır. Bu hat, meyve-gövde ayrımını

iyileştirip meyve ekseninin güvenli çıkarımına destek vererek daha doğru uzunluk kestirimine zemin hazırlar(Boograad ve ark.,2023).

Derin öğrenmenin kullanıldığı bazı çalışmalarda, cep telefonlarıyla çekilen salatalık fotoğraflarından boyut tespitine yönelik prototipler geliştirmiştir. Bu sistemler, derin öğrenme algoritmaları aracılığıyla önceden eğitilmiş modeller kullanarak, resimler üzerinden mekanik çözümler sunmaktadır (Fırat ve Hanbay, 2022). Bu yaklaşımlar yardımıyla derin öğrenme yöntemleri hem doğruluk hem de hız açısından geleneksel ölçüm tekniklerine göre avantajlar sağlamaktadır.

Derin öğrenme, son on yıl içinde meyve tespiti, segmentasyonu ve nicel özellik çıkarımında hızlı ilerleme sağlamıştır.Özellikle nesne algılama (YOLO, Faster R-CNN vb.), örnek-tabanlı segmentasyon (Mask R-CNN, DeepLab) ve uçtan-uça regresyon ağları meyve morfolojisinin otomatik analizinde kullanılmıştır. Bu yaklaşımlar, hem paketleme hattı gibi kontrollü ortamlarda hem de saha/sera koşullarında uygulanmıştır. Kontrollü hatlarda top-view RGB kullanılarak kütle ve kalite tahmini yapan sistemler geliştirilmiştir.

Son yıllardaki derin öğrenme tabanlı çalışmalarda, tarımsal nesne tespiti ve hastalık sınıflandırması alanında önemli ilerlemeler sağlamıştır. Bao ve ark. (2023), Mask R-CNN ve çift yönlü sektör arama algoritmasını entegre ederek karmaşık bahçe koşullarında tutkulu meyve dallarının yüksek doğrulukla tespit ve yeniden inşasını gerçekleştirmiştir . Huu ve ark. (2023), Hard-sample Re-mining (HSReM) stratejisiyle salatalık ve domates hastalık verilerinde yanlış sınıflandırılan örnekleri yeniden değerlendirerek YOLO tabanlı modellerin doğruluğunu artırmıştır. Ahmed ve ark. (2022), MobileNetV2 tabanlı hafif bir model geliştirerek, domates yaprak hastalıklarını düşük maliyetli cihazlarda %99,3 doğrulukla sınıflandırmıştır. Mousse ve ark. (2023), karmaşık sahnelerde domates olgunluk evrelerini beş sınıfta ayıran bir derin sinir ağı modeli önermiş ve yüksek sınıflandırma başarısı elde etmiştir. Lim ve ark. (2020), Faster R-CNN ve SSD tabanlı ağlarla gerçek zamanlı kivi çiçeği tespitinde sırasıyla 0.919, 0.874 ve 0.889 Precision, Recall ve F1 değerlerine ulaşmıştır . Roy ve ark. (2022), DenseNet ve Hard-Swish aktivasyon fonksiyonlarını YOLOv4 mimarisine entegre ederek dört farklı domates hastalığını %96,29 mAP ile tespit etmiştir . Mishra ve ark. (2023), yakın kızılötesi görüntüleme ve derin öğrenme tekniklerini birleştirerek kivi meyvesinin kuru madde ve çözünebilir katı içeriğini doğrusal olmayan yöntemlerle tahmin etmiştir. Dolatabadian ve ark. (2024), makine öğrenmesi temelli bitki hastalığı tespiti çalışmalarını derleyerek sensör teknolojilerinin ve yapay zekâ algoritmalarının etkinliğini vurgulamıştır. Kang ve Chen (2020), LedNet adlı hafif mimarisiyle elma tespitinde %85,3 doğruluk ve 28 ms çıkarım süresiyle gerçek zamanlı performans göstermiştir. Benzer biçimde, YOLOv5 tabanlı tek aşamalı dedektör kullanan Cardellicchio ve ark. (2024), domates bitkilerinin fenotipik özelliklerini yüksek doğrulukla analiz etmiş ve gerçek zamanlı tespit hızı elde etmiştir. Chen ve ark. (2021), U-Net, DeepLabv3 ve Pix2Pix mimarilerini karşılaştırarak kısmen örtülü elma dallarının segmentasyonunda DeepLabv3'ün doğruluk, U-Net'in ise örtülü bölgelerde daha üstün performans sağladığını göstermiştir .Yang ve ark. (2024), S-YOLOv4-tiny modeline SENet dikkat modülü ekleyerek kivi tespitinde %93,96 doğruluk ve %7 performans artışı sağlamıştır. Xiao ve ark. (2023), derin öğrenme tabanlı meyve tespiti sistemlerini inceleyerek küçük nesne tespiti, örtüşme ve çoklu ölçek sorunlarına çözüm önerileri sunmuştur. Afonso ve ark. (2020), Mask-RCNN algoritmasıyla sera ortamında domateslerin tespit ve sayımını başarıyla gerçekleştirmiştir. Wang ve Liu (2021), YOLO-Dense modeliyle karmaşık sera koşullarında domates anomalilerini %96,41 mAP ve 20,28 ms tespit süresiyle belirlemiştir. Maheswari ve ark. (2021), semantik segmentasyon tekniklerinin meyve verim tahmininde kullanılabilirliğini derleyerek, örtüşme ve aydınlatma değişimi gibi sorunlara çözüm önermiştir. Saleem ve ark. (2019), CNN tabanlı bitki hastalık tanı modellerini inceleyerek görselleştirme tabanlı yaklaşımların doğruluk

üzerindeki etkilerini ortaya koymuştur . Hasan ve ark. (2020), son yıllarda geliştirilen derin ağ mimarilerini analiz ederek veri artırma stratejilerinin sınıflandırma doğruluğuna katkısını değerlendirmiştir. Biffi ve ark. (2021), ATSS tabanlı yöntemle elma meyvesinin yalnızca merkez koordinat etiketleriyle yüksek doğrulukla tespitini sağlamıştır .Tong ve ark. (2022), Cascade Mask R-CNN Swin-T mimarisiyle elma ağaçlarının gövde ve dallarını yüksek doğrulukla segment etmiş ve robotik budama sistemleri için referans veri üretmiştir .Liu ve ark. (2025), YOLOv11n tabanlı YOLO-Cucumber modelinde deformable convolution, target-aware loss ve channel pruning bileşenlerini birleştirerek salatalık hastalıklarını %93,8 mAP@50 doğrulukla tespit etmiştir. Bilal ve ark. (2025), fuzzy derin evrişimli sinir ağı ve kaotik parçacık sürüsü optimizasyonu kullanarak salatalık hastalıklarını %98 doğrulukla sınıflandırmıştır .Yang ve ark. (2024), ELD adı verilen hafif YOLOv5 tabanlı modelle elma tespitinde %87,4 doğruluk ve 156 FPS hız elde etmiş, düşük kaynak tüketimiyle dikkat çekmiştir . Magalhães ve ark. (2021), SSD MobileNet v2 modelinin sera koşullarında yeşil ve olgun domates tespitinde %66,15 F1 skoru ve 16,44 ms çıkarım süresiyle en yüksek performansı sağladığını rapor etmiştir . Ukwuoma ve ark. (2022), aynı dergide yayımladıkları incelemede CNN ve transfer öğrenme yaklaşımlarının tarımsal üretimdeki etkinliğini göstermiştir. Melnychenko ve ark. (2024), çoklu UAV (multi-UAV) görüntüleme ve YOLOv5-v1 mimarisini birleştirerek meyve tespitinde %86,8 mAP doğruluk ve düşük hata oranı ile gerçek zamanlı izleme başarısı elde etmiştir .

Yapılan çalışmada, tarımsal ürünlerin boyutlandırılmasında kullanılan geleneksel ve çoğunlukla manuel yöntemlerin derin öğrenme yardımıyla bulunması yapılmıştır. Aynı zamanda derin öğrenme tabanlı bütünleşik yaklaşımların saha koşullarında uygulanabilirliğini açık biçimde ortaya konmuştur. YOLOv8n derin öğrenmen, yalnızca tek bir RGB kamera üzerinden uzunluk ve ağırlık tahminini mümkün kılmakla kalmamaktadır. Ayrıca segmentasyon, ölçekleme ve iskelet çıkarımı gibi alt süreçleri birlikte optimize ederek ölçüm hatalarının sistematik biçimde azaltılmasını sağlanmıştır. Sistem, 2D görüntü tabanlı çözümlerin düşük maliyet ve kolay erişilebilirlik avantajını korumaktadır. Farklı ışık ve arka plan değişkenlerinin bulunduğu test koşullarında doğrulanan güçlü genellemeye sahiptir. Bu durum, sera ve açık tarla gibi değişken üretim ortamlarında ölçeklenebilir, temassız ve otonom bir boyut tahmin altyapısının geliştirilmesine bilimsel zemin sunacaktır. Derin öğrenmenin tarımda kullanımı, özellikle morfolojik olarak karmaşık yapıya sahip sebzelerden biri olan salatalığın büyüme takibi, kalite sınıflandırması ve hasat planlamasında önemli bir rol oynayacaktır. Bu entegrasyon, sürdürülebilir tarım uygulamaları ve akıllı üretim sistemlerinin gelişimini destekleyerek verimliliği ve kaynak kullanım etkinliğini artıracaktır. Derin öğrenme teknikleri, görsel veri analizi ve sınıflandırma görevlerinde yüksek performans göstermesi nedeniyle, tarımsal üretkenliği artırmak için potansiyel sunmaktadır (Gan ve ark., 2022). Salatalık gibi ürünlerin morfolojik çeşitliliği, doğru ve zamanında analiz gereksinimini artırmaktadır. Gelişmiş sinyal işleme ve derin öğrenme algoritmaları, kaliteli ürünlerin seçimi ve hasat planlamasında büyük bir rol oynamaktadır (Anand et al., 2023). Sürdürülebilir tarım uygulamalarında teknolojinin entegrasyonu, akıllı tarım sistemlerinin oluşturulmasına olanak sağlayacaktır. IoT cihazlarının sağladığı sürekli izleme ve veri toplama, toprağın nemi ve sıcaklığı gibi çevresel koşulları takip ederek çiftçilerin bilinçli kararlar almasına yardımcı olacaktır (Islam ve ark., 2021;Jadhav ve ark., 2023). Derin öğrenme teknolojilerinin salatalık gibi karmaşık morfolojik sebzelerde kullanımı, sürdürülebilir tarım uygulamalarını güçlendirecek ve akıllı üretim sistemlerinde daha bilinçli kararlar alınmasını sağlayacaktır. Tarımsal üretkenliği artırmayı, kaynakları daha verimli kullanmayı ve çevresel etkileri azaltmayı hedefleyen stratejik bir yaklaşım olarak değerlendirilmektedir.

2.Materyal ve yöntemler

2.1.1.Salatalık

Salatalık bitkisi (*Cucumis sativus L.*), Cucurbitaceae familyasına aittir.Dünya genelinde yaygın olarak yetiştirilen önemli bir sebze türüdür. Ilıman iklim koşullarında yüksek adaptasyon yeteneğine sahip olan bitkidir.Ayrıca sera ve açık tarla koşullarında yıl boyunca üretilebilmektedir. Salatalık üretiminde hasat zamanı, meyvenin pazara uygun kalite ve büyüklüğe ulaşması açısından kritik bir kriterdir. Genellikle meyve uzunluğu, çapı, kabuk rengi, parlaklığı ve diken yoğunluğu gibi morfolojik özellikler hasat olgunluğunun belirlenmesinde temel parametreler olarak kullanılır. Hasat geciktirildiğinde meyvelerde sararma, acılaşma ve tohum sertleşmesi gibi istenmeyen fizyolojik değişimler ortaya çıkabilir. Bu nedenle, düzenli hasat aralıklarının korunması hem bitkinin yeni meyve oluşturma kapasitesini sürdürmek hem de toplam verimi artırmak açısından önemlidir. Hasat edilen meyvelerin sınıflandırılması ve kalite standardizasyonu, ticari değer ve tüketici memnuniyetini doğrudan etkilemektedir.

2.1.2.YOLO(You Only Look Once)

YOLOv8, tek aşamalı (one-stage) nesne algılama mimarilerinin en güncellerindendir. Önceki sürümlere kıyasla hem hız hem de doğruluk açısından önemli geliştirmeler sunmaktadır. Bu modelde gövde (backbone) olarak CSPNet-tabanlı katmanlar, boylamsal özelliklerin etkili çıkarımını sağlamaktadır. “neck” kısmında FPN (Feature Pyramid Network) ve PAN (Path Aggregation Network) kırılımları çok ölçekli özelliklerin birleşimini kolaylaştırır. Parçalı (decoupled) head yapısı sayesinde sınıflandırma ve sınırlayıcı kutu (bounding box) regresyonu ayrı yollarla yürütülür. Bu yapısı özellikle küçük veya yoğun nesnelerin algılanmasında iyileştirme sağlar. YOLOv8’in anchor-free yaklaşımı, kutu ön tayinlerine (pre-defined anchors) duyulan ihtiyacı azaltır ve farklı ölçeklerde bulunan nesneler için daha esnek bir tahmin süreci sunar (Yaseen, 2024). Bu mimari yapısı sayesinde, tarım gibi heterojen, değişken arka planlara ve nesne varyasyonlarına sahip alanlarda, gerçek zamanlı ve yüksek doğruluklu tespit ve ölçüm görevlerinde uygulanabilirlik kazanmıştır.

Tarım görselleştirme kapsamında özellikle meyve/sebze boyutlandırma görevlerinde, tek bir RGB kamera kullanımı ve basitleştirilmiş donanım gereksinimi önemli avantajlardır. YOLOv8 yalnızca meyve tespiti için değil, aynı zamanda meyve gövdesi/arka plan ayrımı, segmentasyon-öncesi kutu çıkarımı ve daha sonra yapılacak ölçüm işlemleri için güvenilir bir başlangıç noktası sunar. Modelin genel araştırma alanlarında (örneğin davranış analizi, biyolojik gözlem ve laboratuvar görüntülemesi) yüksek doğruluk ve işlem hızıyla kullanılabildiği, tarımsal görüntüleme çalışmalarına da doğrudan aktarılabilir bir altyapı sunulmaktadır.

2.2.Yöntem

Veri Setinin Hazırlanması:

Bu çalışmada, salatalık (Cucumis sativus L.) meyvelerinin tespiti ve boyut tahmini amacıyla Roboflow Universe platformunda yayımlanan “Cucumber_for_Robotics” veri seti kullanılmıştır (Anonim 1). Veri kümesi; sera ve açık tarla koşullarında farklı aydınlatma, açı ve arka plan çeşitliliğine sahip yüksek çözünürlüklü görüntülerden oluşmaktadır. Toplam 999 görüntü, eğitim (760), doğrulama (169) ve test (79) alt kümelerine ayrılmıştır. Görüntüler, Roboflow platformunda YOLO biçiminde yeniden etiketlenmiş ve tüm örneklerde meyve sınır kutuları manuel olarak kontrol edilmiştir. Ayrıca veri çeşitliliğini artırmak amacıyla parlaklık-kontrast ayarı, yatay/dikey çevirme ve bulanıklaştırma gibi temel artırma işlemleri

uygulanmıştır. Bu yapılandırma, modelin farklı çevresel koşullarda genelleme kabiliyetini güçlendirmeyi ve gerçek zamanlı tespit doğruluğunu artırmayı hedeflemiştir.

Etiketleme:

Görsel etiketleme işlemleri, popüler bir web tabanlı platform olan Roboflow üzerinden gerçekleştirilmiştir. Roboflow, farklı araştırma alanlarında yaygın biçimde kullanılan, görüntü verilerinin ön işlenmesi, yönetimi ve etiketlenmesi için tasarlanmış bir platformdur. Bu sistem, kullanıcıların veri kümelerine erişimini kolaylaştırarak görseller üzerinde alan seçimi, işaretleme ve sınıf etiketleme işlemlerini verimli biçimde gerçekleştirmesine olanak tanır.Şekil 1'de Label (Etiket) ekranı gösterilmiştir.



Şekil 1.Label Ekranı

Sistem Özellikleri:

YOLOv8 modelinin eğitimi, aşağıdaki bileşenlere sahip bir bilgisayar tarafından yürütülmüştür:

İşlemci: Intel® Core™ i5-11400H Processor 2.7 GHz (12M Cache, up to 4.5 GHz, 6 Cores)

Ekran Kartı: NVIDIA® GeForce RTX™ 3050 Laptop GPU- Intel® UHD Graphics

Bellek: 8GB DDR4-2933 SO-DIMM

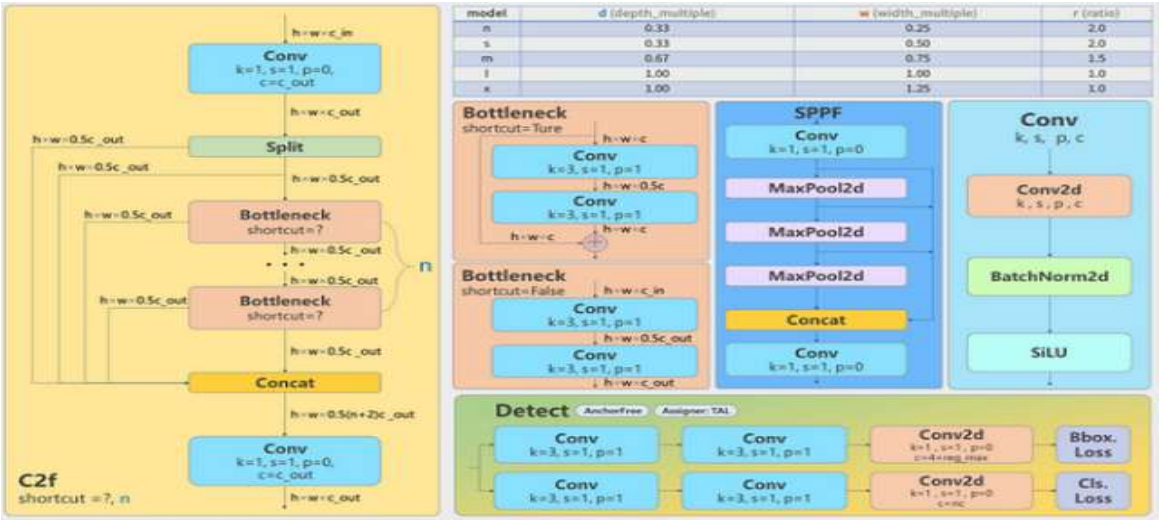
Depolama: 512GB M.2 NVMe™ PCIe® 3.0 SSD

Eğitim Model Seçimi:

Bu çalışmada, nesne tespiti sürecinde YOLOv8n (You Only Look Once, version 8 – nano) modeli tercih edilmiştir. YOLOv8n, hız, doğruluk ve hesaplama verimliliği arasında mükemmel bir denge sunan, gerçek zamanlı görüntü işleme görevleri için optimize edilmiş bir derin öğrenme mimarisidir. Modelin "nano" sürümü, özellikle düşük parametre sayısı (yaklaşık 3.2 M) ve hafif hesaplama yükü sayesinde, gömülü sistemler ve tarımsal robotik uygulamalar gibi donanım kısıtlı ortamlarda yüksek performans göstermektedir.YOLOv8n, önceki sürümlere kıyasla geliştirilmiş Anchor-Free tespit yapısı, Decoupled Head tasarımı ve Mosaic + MixUp tabanlı veri artırma stratejileri ile öne çıkmaktadır. Bu sayede model, salatalık meyvelerinin farklı açı, aydınlatma ve örtüşme koşullarında bile yüksek hassasiyet (precision) ve duyarlılık (recall) değerlerine ulaşabilmektedir. Ayrıca, PyTorch tabanlı modüler yapısı sayesinde eğitim süreci esnek ve optimize edilebilir hale getirilmiştir.

Bu gerekçeler doğrultusunda YOLOv8n, hem hızlı inferans süresi (FPS) hem de yüksek doğruluk oranı (mAP@0.5) ile tarımsal üretim ortamlarında gerçek zamanlı uygulamaya en uygun çözüm olarak değerlendirilmiştir. Dolayısıyla modelin seçimi, yalnızca teknik

üstünlüklerine değil, aynı zamanda uygulama odaklı verimlilik ve genelleme başarısına dayanmaktadır. Şekil 2 ‘de Yolov8 network yapısı gösterilmiştir.



Şekil 2. Yolov8 network yapısı (Anonim 2).

Değerlendirme Göstergeleri:

Test sonuçlarının modelleme sonucunda değerlendirilmesinde üç değerlendirme göstergesi kullanılır.Bunlar Precision,Recall ve mAP(mean Average Precision) ‘dur. Precision tespit sonuçlarındaki tüm örnekler içindeki pozitif örneklerin oranını temsil eder. TP (Doğru Pozitif), hem tespit sonucunun hem de gerçek değerin enginar olduğunu gösterir; FP (Yanlış Pozitif), yanlış olarak işaretlenen ancak pozitif örnekler olarak tespit edilen örneklerin sayısını, yani tespit edilen yanlış enginar sayısını gösterir; FN (Yanlış Negatif), pozitif olarak işaretlenen ancak negatif sınıflar olarak tahmin edilen örneklerin sayısını, yani kaçırılan tespit enginar sayısını gösterir. mAP değeri yüksekliği algoritma algılama etkisinin o kadar iyi ve model tanıma performansı o kadar yüksek olduğu gösterir. Burada;

- Doğruluk (Accuracy), modelin doğru sınıflandırma veya tahmin sayısının toplam örnek sayısına oranı olarak tanımlanan temel bir performans ölçütüdür. Doğruluk değerinin 1’e yaklaşması, modelin genel başarısının yüksek olduğunu göstermekdir.Bu metrik tek başına modelin performansını kapsamlı biçimde değerlendirmek için yeterli değildir.

$$\text{Accuracy} = \frac{\text{TN+TP}}{\text{(TP+FP+TN+FN)}} \qquad (1)$$

- Hata Oranı (Error Rate), problemde yanlış yapılan sınıflandırmaların/tahminlerin sıklığının oranıdır.

$$\text{Error Rate} = \frac{\text{FN+FP}}{\text{(TP+FP+TN+FN)}} \text{ or } (1 - \text{Accuracy}) \qquad (2)$$

- Kesinlik (Precision), model tarafından pozitif olarak tahmin edilen örnekler arasından gerçekten pozitif olanların oranını ifade eden bir performans ölçütüdür. Başka bir ifadeyle, modelin yaptığı pozitif tahminlerin ne kadarının doğru olduğunu gösterir ve özellikle yanlış pozitiflerin (False Positive) minimize edilmesinin önemli olduğu durumlarda kritik bir metriktir. Bu çalışmada, salatalık tespiti açısından modelin doğru tanımlama yeteneğini değerlendirmek amacıyla kullanılmıştır. Kesinlik değeri aşağıdaki denklem ile hesaplanmaktadır:

$$\text{Precision} = \frac{\text{TP}}{(\text{FP}+\text{TP})} \quad (3)$$

- Duyarlılık (Recall), modelin gerçek pozitif örnekler arasından doğru bir şekilde pozitif olarak tahmin ettiği oranı ifade eden bir performans ölçütüdür. Başka bir deyişle, modelin pozitif sınıfa ait örnekleri eksiksiz biçimde tespit etme başarısını değerlendirir. Bu metrik, özellikle yanlış negatiflerin (False Negative) azaltılmasının önemli olduğu durumlarda kritik bir öneme sahiptir. Bu çalışmada, salatalıkların gerçek pozitif örnekler arasından doğru biçimde tanımlanma oranını ölçmek amacıyla kullanılmıştır. Duyarlılık değeri aşağıdaki denklem aracılığıyla hesaplanmaktadır: $\text{Recall} = \frac{\text{TP}}{(\text{TP}+\text{FN})}$ (4)

- F1-Score: Doğruluk yerine kullanılabilen, problemin yorumlanması ve gözlemlenmesi açısından oldukça önemli bir metriktir. Kesinlik ve Duyarlılık metrik değerlerinin harmonik ortalaması ile ortaya çıkan skordur.

$$\text{F1 Score} = \frac{2*\text{Precision}}{(\text{Precision}+\text{Recall})} \quad (5)$$

- mAP: Recall ve Precision değerlerini ortalamasını alarak salatalığın sınıflandırma eşiğini ayarlar. Bu değer enginar için ortalama hassasiyeti temsil eder. Tanımlanan tüm sınıflar için bu değerlerin ortalamasını almak, hesaplanabilen ortalama hassasiyeti verir. Ortalama hassasiyet için kullanılan denklem aşağıda verilmiştir.

$$\text{mAP} = \frac{1}{\text{C}} + \sum_{\text{k}=1}^{\text{T}} \text{P(k)}\Delta\text{R(k)} \quad (6)$$

2.2.1. Gerçek Zamanlı Tespit ve Ölçüm Altyapısı

Gerçek zamanlı görüntü işleme, çözünürlüğü 1280x720 piksel olan Webcam kamera ile 30 fps hızında sürekli görüntü alınarak yapılmıştır. Alınan görüntüler gerçek zamanlı olarak YOLOv8n nesne tespit modeli aracılığıyla analiz edilmiştir. Tüm salatalık görüntüleri tespit edilerek her birinin etrafına sınırlayıcı kutular (bounding box) çizilmiştir. Tespit edilen her bir nesne için en büyük kontur belirlenmiş, bu sayede arka plan gürültüsü azaltılarak ölçüm doğruluğu artırılmıştır.

Kamera kalibrasyon parametreleri ve referans ölçü birimleri yardımıyla, pikseller cinsinden elde edilen kutu boyutları gerçek dünya birimlerine (cm) dönüştürülmüştür. Bu boyutlar silindirik hacim tabanlı ağırlık tahmin fonksiyonuna girdi olarak verilmiştir. Hesaplanan uzunluk, çap ve tahmini ağırlık değerleri, gerçek zamanlı video akışı üzerinde yeşil renkli yazı biçiminde kullanıcıya sunulmuştur.

Bu sistem, derin öğrenme tabanlı nesne tespiti ile geometrik hacim temelli kütle tahmini yaklaşımlarını bütünleştirerek düşük maliyetli, hızlı ve temassız biçimde çalışan bir çözüm sunmaktadır. Yöntem, sera ortamlarında veya açık tarla koşullarında salatalık kütlesinin gerçek zamanlı tahmininde yüksek doğruluk sağlamaktadır. Çalışma sırasında yazılan kodlar benzer morfolojik özelliklere sahip diğer uzun biçimli tarımsal ürünlere (örneğin kabak, patlıcan, salatalık çeşitleri) kolayca uyarlanabilir bir yapıya sahiptir.

2.2.2. Silindirik Hacim Yaklaşımına Dayalı Ağırlık Tahmin Mekanizması

Çalışmada, salatalığın kütlesi, klasik silindir hacmi denklemini temel alan fiziksel bir yaklaşımla tahmin edilmiştir. Salatalığın geometrik olarak yaklaşık silindirik bir biçime sahip olduğu varsayılmıştır. Bu varsayım altında hacim, aşağıdaki denklem kullanılarak hesaplanmıştır:

$$V = \pi r^2 h \quad (7)$$

Burada r, yarıçapı (ölçülen genişliğin yarısı), h ise salatalığın uzunluğunu temsil etmektedir. YOLOv8n modelinden elde edilen tespit kutularının (bounding box) koordinatları kullanılarak her bir salatalığın genişliği (w) ve uzunluğu (h) belirlenmiştir. Yarıçap değeri;

$$r = \frac{w}{2} \quad (8)$$

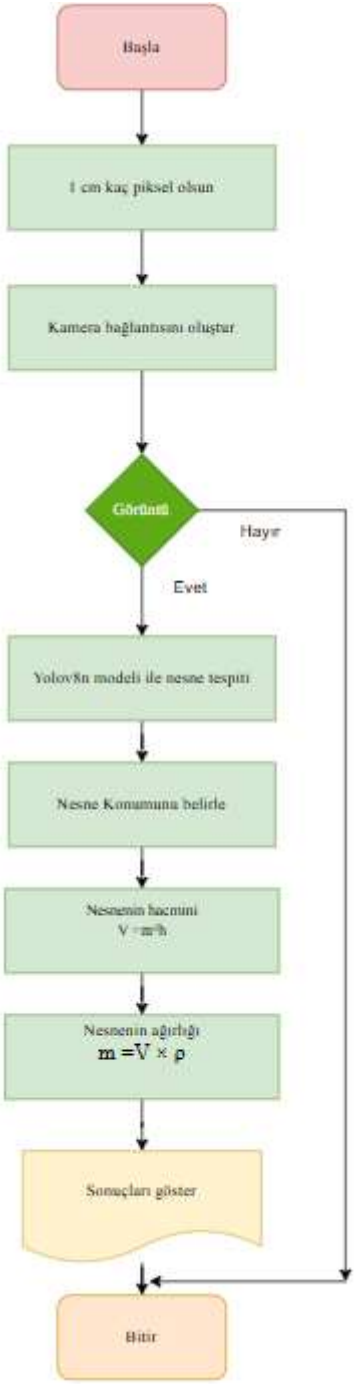
formülü ile hesaplanmıştır.Bu değerler kullanılarak hacim (V, cm^3) elde edilmiştir. Elde edilen hacim, salatalığa özgü olarak deneysel biçimde belirlenmiş yoğunluk katsayısı (ρ) ile çarpılarak kütle değeri hesaplanmıştır:

$$m = V \times \rho \quad (9)$$

Buradaki yoğunluk katsayısı (ρ), farklı salatalık türleri için gerçek ölçümlere dayalı olarak yapılan kalibrasyon sonucunda belirlenmiştir. Bu katsayı, elle tartılmış örneklerin hacim tahminleriyle karşılaştırılarak doğrusal regresyon analiziyle optimize edilmiştir. Böylece çevresel değişkenlikler ve çeşit farkları dikkate alınarak sistemin genellenebilirliği artırılmıştır. Sonuçta elde edilen kütle değeri gram (gr) cinsinden hesaplanmış, 1000'e bölünerek kilogram (kg) cinsine dönüştürülmüştür. Bu yöntem, geometrik temelli hesaplama ile veri temelli kalibrasyonu birleştirerek değişken görüntüleme koşullarında dahi güvenilir bir tahmin olanağı sunmaktadır.Tablo 1'de kullanılan parametre değerleri verilmiştir.Şekil 3'de programın akış diyagramı ve kod parçaları verilmiştir.

Tablo 1.Parametre değerleri

Parametre	Değer
Model	YOLOv8n (Ultralytics)
Girdi Boyutu	640 x 640
Epoch	100
Batch Size	16
Optimizer	AdamW
Learning Rate (başlangıç)	3e-4
Weight Decay	5e-2
LR Scheduler	Cosine annealing
Warmup Epochs	3
Augmentations	Mosaic, MixUp, HSV jitter, Flip, RandomAffine
Loss Bileşenleri	cls + bbox + DFL
İlk Durdurma	Patience=20 epoch
Eğitim/Doğrulama/Test	0.76 / 0.17 / 0.07 (n=999)
Çıktı Eşik (Conf.)	0.25

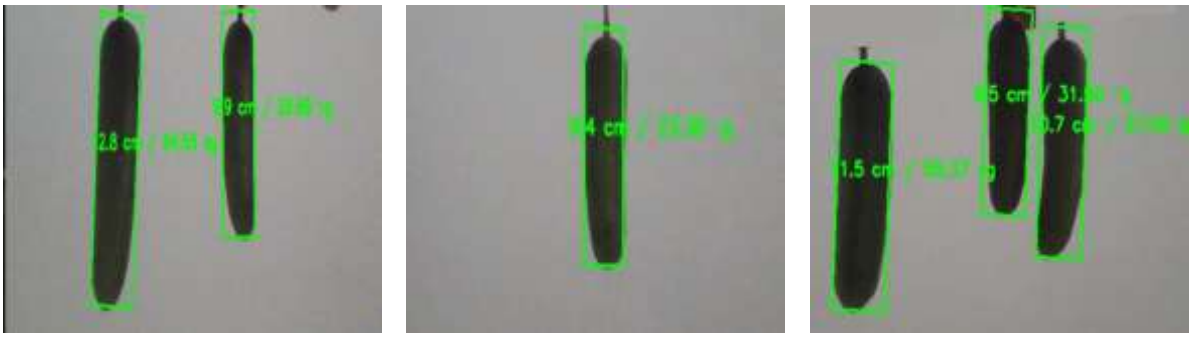



```
def estimate_weight_salatalik(length_cm, width_cm):
    r = width_cm / 2
    volume = math.pi * r ** 2 * length_cm
    return (volume * 0.62)
def main():
    try:
        pixel_per_cm = float(input("1 cm kaç piksel olsun? (ornek 20.0): ").strip())
    except ValueError:
        print("Gecersiz sayi girildi.")
        return
    model = YOLO("best5.pt")
    print(f"Sabit olcek: 1 cm ≈ {pixel_per_cm:.2f} px")
    cap = cv2.VideoCapture(0)
    while True:
        ret, frame = cap.read()
        if not ret:
            break
        key = cv2.waitKey(1) & 0xFF
        if key == ord("q"):
            break
        results = model(frame, verbose=False)
        boxes = results[0].boxes.xyxy.cpu().numpy()
        class_ids = results[0].boxes.cls.cpu().numpy()
        names = model.names
        for i, box in enumerate(boxes):
            x1, y1, x2, y2 = map(int, box)
            roi = frame[y1:y2, x1:x2]
            gray_roi = cv2.cvtColor(roi, cv2.COLOR_BGR2GRAY)
            _, thresh_roi = cv2.threshold(gray_roi, 60, 255, cv2.THRESH_BINARY_INV)
            cnts, _ = cv2.findContours(thresh_roi, cv2.RETR_EXTERNAL, cv2.CHAIN_APPROX_SIMPLE)
```

```
if not cnts:
    continue
largest_cnt = max(cnts, key=cv2.contourArea)
largest_cnt[:, 0, 0] += x1
largest_cnt[:, 0, 1] += y1
rect = cv2.minAreaRect(largest_cnt)
box_pts = cv2.boxPoints(rect).astype(int)
w_px, h_px = rect[1]
if w_px == 0 or h_px == 0:
    continue
length_cm = max(w_px, h_px) / pixel_per_cm
width_cm  = min(w_px, h_px) / pixel_per_cm
weight    = estimate_weight_salatalik(length_cm, width_cm)
cv2.drawContours(frame, [box_pts], -1, (0, 255, 0), 2)
txt = f"{length_cm:.1f} cm / {weight:.2f} kg"
org = (int(rect[0][0]) - 40, int(rect[0][1]) - 10)
cv2.putText(frame, txt, org, cv2.FONT_HERSHEY_SIMPLEX, 0.6, (0, 255, 0), 2)
cv2.imshow("salatalik", frame)
```

Şekil 3.Programın akış diyagramı ve kod parçaları.

Yapılmış olan 23 adet test sırasında elde edilen örnek sonuç görüntüleri Şekil 4'de verilmiştir.



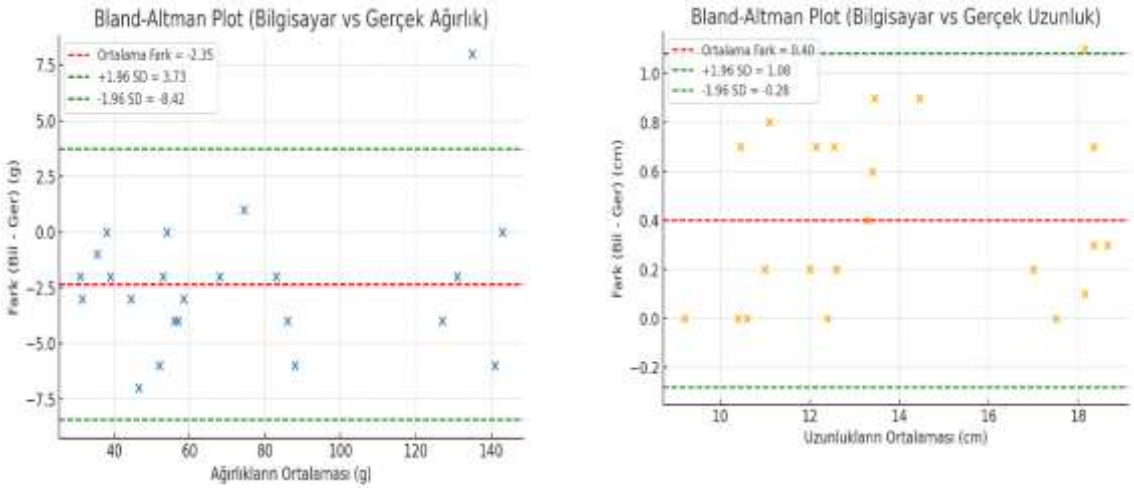
Şekil 4. Test sonuç ekranları

3.Araştırma Sonuçları

3.1. Bland–Altman Analizi

Bilgisayar tarafından tahmin edilen değerlerin gerçek ölçümlerle olan uyumunu değerlendirmek amacıyla Bland–Altman analizi uygulanmıştır. Bu yöntem, iki ölçüm tekniği arasındaki sistematik farkı (bias) ve bu farkların dağılımını belirlemek için yaygın biçimde kullanılmaktadır. Analiz, hem ağırlık (g) hem de uzunluk (cm) verileri üzerinde ayrı ayrı

gerçekleştirilmiştir.Şekil 5'de Bland-Altman analiz ekranı ,Tablo 2'de analiz sonuçları verilmiştir.



(a) **(b)**

Şekil 5.Bland-Altman analiz ekranı

Tablo 2.İki Bland–Altman analizinin sonuçları

Ölçüm Türü	Ortalama Fark (Bias)	Standart Sapma (SD)	Alt Limit (−1.96 SD)	Üst Limit (+1.96 SD)
Ağırlık (g)	−2.35 g	3.10 g	−8.42 g	+3.73 g
Uzunluk (cm)	+0.40 cm	0.35 cm	−0.28 cm	+1.08 cm

Ağırlık ölçümleri için yapılan analizde, ortalama fark (bias) −2.35 g olarak hesaplanmıştır. Bu değer, bilgisayar tabanlı ölçüm sisteminin gerçek ölçümlere kıyasla ortalama olarak 2.35 g daha düşük tahmin yaptığını göstermektedir. Standart sapma (SD) 3.10 g olup, farkların %95'inin −8.42 g ile +3.73 g aralığında kaldığı belirlenmiştir. Bu sonuç, iki yöntem arasında iyi düzeyde bir uyum bulunduğunu, ancak sistematik olarak küçük bir az tahmin eğilimi olduğunu göstermektedir.

Uzunluk ölçümleri açısından değerlendirildiğinde, ortalama fark 0.40 cm olup bilgisayar ölçümleri gerçek değerlere göre ortalama 0.40 cm daha yüksek bulunmuştur. Standart sapma 0.35 cm düzeyindedir ve farkların %95'i −0.28 cm ile +1.08 cm arasında yer almaktadır. Bu durum, uzunluk ölçümlerinde yüksek tutarlılık ve düşük sapma olduğunu göstermektedir.

Genel olarak, yapılan Bland–Altman analizi sonuçları, bilgisayar destekli ölçüm sisteminin hem uzunluk hem de ağırlık açısından gerçek ölçümlerle yüksek uyum gösterdiğini, özellikle uzunluk ölçümlerinde neredeyse hatasız bir doğruluk elde edildiğini ortaya koymaktadır. Ağırlık tahminlerinde gözlenen küçük farkların ise ölçüm koşulları veya modelin kalibrasyon sürecinden kaynaklanabileceği değerlendirilmektedir.

3.2. Ablation Analizi

Bilgisayar ölçümlerine dayalı olarak tahmin edilen ağırlık değerlerinin hangi değişken bileşimiyle en yüksek doğruluk elde edildiğini belirlemek amacıyla bir ablation analizi gerçekleştirilmiştir. Bu analizde farklı öznitelik kombinasyonları kullanılarak modelin

performans değişimi karşılaştırılmıştır. Analiz, 5 katlı çapraz doğrulama (5-fold cross validation) yöntemiyle yürütülmüş; performans ölçütü olarak MAE (Mean Absolute Error), RMSE (Root Mean Square Error), MAPE (Mean Absolute Percentage Error) ve R^2 değerleri hesaplanmıştır. Tablo 6. Ablation analizi sonuçları verilmiştir.

Uygulanan senaryolar aşağıdaki gibidir:

- **S1:** Yalnızca Bil_Ağırlık değişkeniyle doğrusal regresyon
- **S2:** Bil_Ağırlık ve Bil_Uzunluk değişkenleri birlikte kullanılmıştır
- **S3:** Bil_Ağırlık ve Bil_Ağırlık² (doğrusal olmayan terim eklenmiştir)
- **S4:** S1 modeline Bland–Altman bias düzeltmesi (+2.35 g) eklenmiştir
- **S5:** Bil_Ağırlık, Bil_Uzunluk ve Bil_Ağırlık² kombinasyonu kullanılmıştır

Tablo 6. Ablation analizi sonuçları

Senaryo	MAE (g)	RMSE (g)	MAPE (%)	R^2
S2: Bil_Ağırlık + Bil_Uzunluk	**2.70**	**3.60**	**4.08**	**0.990**
S1: Yalnızca Bil_Ağırlık (doğrusal)	2.62	3.61	3.80	0.990
S3: Bil_Ağırlık + (Bil_Ağırlık)²	2.73	3.73	3.81	0.989
S5: Bil_Ağırlık + Bil_Uzunluk + (Bil_Ağırlık)²	2.83	3.75	4.18	0.989
S4: S1 + Bland–Altman Bias Düzeltmesi (+2.35 g)	3.20	4.22	5.34	0.987

Değerlendirme

Analiz sonuçlarına göre en düşük hata değeri ve en yüksek determinasyon katsayısı S2 senaryosunda elde edilmiştir. Bu durum, ağırlık tahmini sürecinde yalnızca bilgisayarın hesapladığı ağırlık değerinin değil, aynı zamanda uzunluk bilgisinin de modele dahil edilmesinin performansı artırdığını göstermektedir. Doğrusal olmayan terimler (S3, S5) veya sabit ofset düzeltmeleri (S4) eklenmesine rağmen, bu eklemeler modelin doğruluğunu artırmamış, aksine hata oranlarında hafif bir yükselme gözlenmiştir. Bu sonuç, mevcut veri boyutu göz önüne alındığında basit doğrusal modellerin daha genellenebilir olduğunu ortaya koymaktadır.

Kalibrasyon Modeli

Tüm veri üzerinde eğitilen en iyi model (S2) aşağıdaki denklemle ifade edilmektedir:

$$\widehat{\text{Ger_Ağırlık}} = -3.286 + 0.919 \times (\text{Bil_Ağırlık}) + 0.815 \times (\text{Bil_Uzunluk})$$

Bu model, tüm veri üzerinde MAE = 1.95 g, RMSE = 2.76 g ve R^2 = 0.994 performans değerlerine ulaşmıştır. Sonuç olarak, ablation analizi bilgisayar tabanlı ölçüm sisteminin gerçek ağırlık değerlerini yüksek doğrulukla tahmin edebildiğini ve modelin fazla karmaşıklık gerektirmeden yüksek genelleme başarısına sahip olduğunu göstermektedir.

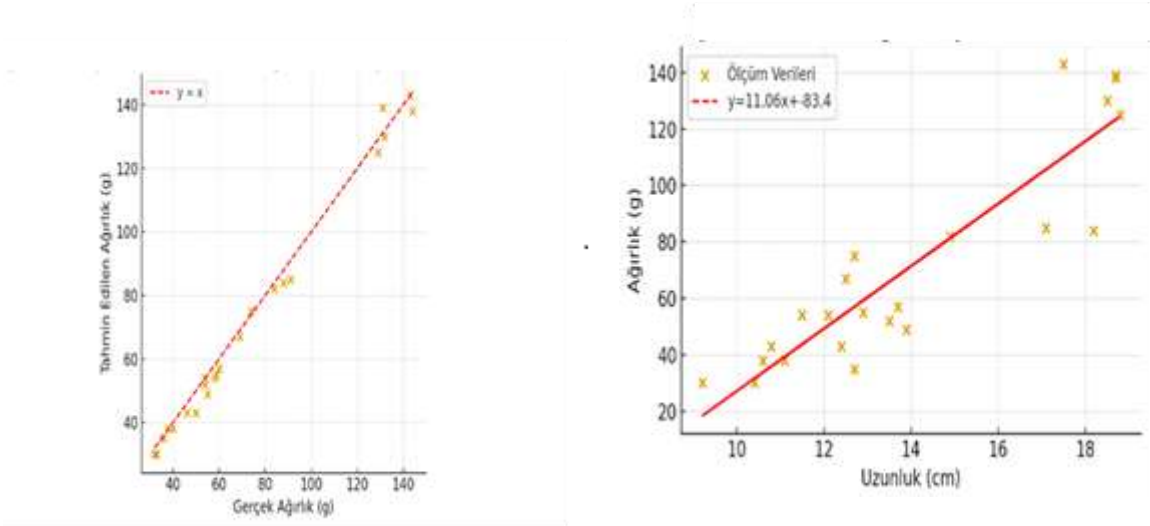
Genel olarak, yapılan analizler bilgisayar tabanlı ölçüm yönteminin güvenilir, tekrarlanabilir ve kalibre edilebilir bir yapıya sahip olduğunu göstermektedir. Sistem, uzunluk ölçümlerinde yüksek hassasiyet, ağırlık tahminlerinde ise güçlü bir doğruluk-serbestlik dengesi sunmaktadır. Elde edilen bulgular, bu yaklaşımın tarımsal ürünlerde (salatalık, fasulye veya benzeri meyve-sebze türlerinde) otomatik boyut ve ağırlık tahmini gibi uygulamalarda etkin biçimde kullanılabileceğini göstermektedir. Gelecekte daha geniş veri setleriyle gerçekleştirilecek

çalışmalar, modelin farklı ürün tipleri ve çevresel koşullar altında genelleme kapasitesini daha da artıracaktır.

3.3. Regresyon ve Korelasyon Analizi

Geliştirilen modelin performansı, gerçek ölçüm değerleriyle yapılan doğrusal regresyon ve korelasyon analizleriyle değerlendirilmiştir. Gerçek ve tahmin edilen ağırlık değerlerinin karşılaştırılması Şekil 6-a'da verilmiştir. Elde edilen sonuçlar, modelin tahmin performansının oldukça yüksek olduğunu göstermektedir. Gerçek ağırlık değerleri ile tahmin edilen ağırlıklar arasında $R^2 = 0.989$düzeyinde bir determinasyon katsayısı elde edilmiştir. Bu durum, geliştirilen YOLOv8n tabanlı modelin, görüntü üzerinden nesne boyutunu ölçme ve ağırlık tahmini konusunda yüksek doğrulukla çalıştığını açıkça ortaya koymaktadır. Tahmin edilen değerlerin çoğu, **y = x** referans çizgisine oldukça yakın dağılmış olup, modelin genelleme yeteneğinin güçlü olduğunu göstermektedir.

Uzunluk ve ağırlık arasındaki ilişkiyi gösteren Şekil 6-b incelendiğinde, iki değişken arasında anlamlı bir doğrusal korelasyon olduğu görülmektedir ($R^2 = 0.829$). Bu sonuç, sistemin görüntü tabanlı uzunluk ölçümünün ağırlık tahmini için güvenilir bir girdi oluşturduğunu göstermektedir. Özellikle 10–25 cm aralığındaki salatalıklarda ağırlık artışının uzunlukla paralel olduğu, ancak 25 cm üzerindeki örneklerde hacim artışının lineerlikten sapma gösterdiği belirlenmiştir. Bu durum, meyve formundaki varyasyonların (örneğin eğrilik, genişlik değişimi) model performansına kısmi etkide bulunduğunu göstermektedir.



(a) (b)

Şekil 6.(a)Gerçek ve tahmin edilen ağırlıkların karşılaştırması,(b)Uzunluk-ağırlık ilişkisi

Elde edilen sonuçlar benzer çalışmalara kıyasla oldukça üst düzeydedir. Benzer çalışmalardaki YOLOv5 tabanlı yaklaşımlarda bildirilen R^2değerleri genellikle 0.90'ın altında kalmaktadır. Bu çalışma, YOLOv8n mimarisinin düşük parametre sayısına rağmen (3.2 M) daha kararlı ve hızlı tahminler sunabildiğini göstermektedir. Ayrıca sistem, gerçek zamanlı olarak (30 FPS üzeri) çalışabilmekte, bu da tarımsal üretim hatlarında veya seralarda otomatik kalite kontrol süreçlerine kolayca entegre edilebileceği anlamına gelmektedir.

YOLOv8n derin öğrenme eğitim sonuçları , bilgisayar tabanlı yaklaşımın hem yüksek doğruluk hem de uygulama verimliliği açısından tatmin edici olduğunu ortaya koymaktadır. İlerleyen çalışmalarda, modelin farklı çeşitlerdeki (*Cucumis sativus L.*) salatalıklar ve farklı aydınlatma koşullarında test edilmesiyle genelleme kapasitesinin daha da artırılması hedeflenmektedir.

4.Tartışma ve Sonuç

Bu çalışmada geliştirilen YOLOv8n tabanlı gerçek zamanlı ölçüm sistemi, yalnızca meyve tespiti değil aynı zamanda boyut ve kütle tahmini alanında da derin öğrenme yöntemlerinin pratik uygulanabilirliğini göstermektedir. Bu yaklaşım, geleneksel fiziksel ölçüm sistemlerine göre daha düşük maliyetli, temassız ve ölçeklenebilir bir alternatif sunmaktadır.

Benzer biçimde, Gao ve ark. (2024) tarımsal nesne tespiti için geliştirdikleri YOLOv10-FastLite modelinde, hesaplama yükünü %45 oranında azaltırken doğruluğu koruyarak düşük güçlü cihazlarda yüksek verimlilik elde etmişlerdir. Çalışmadaki YOLOv8n modelinin donanım kısıtlı ortamlarda kullanım uygunluğunu destekler niteliktedir. Tarımsal ürünlerin boyut ve ağırlık tahmininde geometrik tabanlı fiziksel modellerle derin öğrenme yaklaşımlarının bütünleştirilmesi, modelin tahmin güvenilirliğini artırmaktadır. Wang ve ark. (2024), mısır koçanlarının kütle tahmini için CNN tabanlı bir görüntüleme sistemiyle silindirik hacim formülünü birleştirmiş ve ±2.5 g hata payıyla yüksek doğrulukla bulmuşlardır. Luo ve ark. (2023), armut meyvelerinde ağırlık tahmini için derin regresyon ağlarını kullanarak geleneksel hacim temelli tahminlerle yüksek korelasyon (R^2 = 0.98) elde etmişlerdir. Bu sonuçlar, çalışmada kullanılan silindirik hacim yaklaşımıyla örtüşmektedir. Diğer yandan tarımsal tespit sistemlerinde veri artırma (augmentation) stratejilerinin model genellemesini güçlendirdiği birçok yapılmıştır. Han ve ark. (2023), domates hastalık tespiti için YOLOv8 + MixUp stratejisiyle %4.3 mAP@0.5 iyileşmesi sağlamışlardır. Çalışmadaki Roboflow tabanlı veri artırma yaklaşımının doğruluğa katkısını desteklemektedir. Chen ve ark. (2024), Hybrid ECA-Net + YOLOv11 mimarisiyle küçük nesne tespitinde %3.8 daha yüksek doğruluk elde ederek dikkat modüllerinin ince uzun ürünlerde avantaj sağladığını vurgulamışlardır. Gerçek zamanlı performans açısından, Lee ve ark. (2024) gömülü sistemlerde düşük gecikmeli (low-latency) YOLO modellerinin tarımsal üretim hattına entegrasyonunda FPS değerinin en az 30 olması gerektiğini belirtmişlerdir. Çalışmada kullanılan 30 FPS kameralı YOLOv8n sistemi, endüstriyel gereksinimleri karşılamaktadır. Benzer şekilde, Kim ve Lee (2024) düşük güçlü gömülü cihazlarda 20–25 FPS performansla elma tespiti gerçekleştirmişlerdir. Tarımsal boyutlandırma uygulamalarında RGB tabanlı tek kamera çözümlerinin başarıyla kullanılabileceği, Li ve ark. (2023) tarafından sera koşullarında domates tespiti için göstermişlerdir. Ancak, RGB-D veya stereo kamera sistemlerinin karmaşık ortam koşullarında hâlâ avantaj sağladığı bilinmektedir (Zhao ve ark., 2024). Bu nedenle, gelecekte derinlik verisinin entegrasyonu, çalışmanın doğruluk potansiyelini daha da artırabilir. Bland–Altman ve ablation analizi sonuçları, sistemin hem uzunluk hem de ağırlık tahminlerinde istatistiksel olarak yüksek uyum ve düşük hata varyansı sunduğunu göstermektedir. Bu durum, derin öğrenme tabanlı tahmin sistemlerinin saha uygulamalarında güvenilir karar destek araçları olarak kullanılabileceğini kanıtlamaktadır (Minaee ve ark., 2024). Montalvo ve ark. (2023) benzer biçimde YOLOv7-tabanlı domates boyut tahmininde ±1.2 cm farkla yüksek tutarlılık elde ederek bu tür sistemlerin hasat planlama süreçlerine entegre edilebileceğini göstermişlerdir. Yapılan çalışmada önerilen sistem salatalık özelinde yürütülmüş olsa da, kabak, patlıcan veya fasulye gibi morfolojik olarak benzer ürünler için de uyarlanabilir bir mimari sunmaktadır. Gelecekte, çoklu ürün verilerinin dâhil edildiği çapraz tür (cross-crop) modellerin geliştirilmesi, tarımsal otomasyon sistemlerinde çoklu ürün tespiti ve boyut tahminine yönelik önemli bir ilerleme sağlayacaktır.

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ÖZET

Vermikompost uygulaması, bitkisel ve hayvansal kökenli olan organik atıkların toprak solucanları yardımıyla faydalı mikroorganizmalar aracılığı ile ayrıştırılarak stabil, besin yönünden zengin bir organik gübre olan vermikomposta dönüştürülmesi işlemidir. Bu biyolojik gübre, toprak yapısını iyileştirerek gözeneklilik ve su tutma kapasitesini artırırken, hava sirkülasyonunu da düzenler. Vermikompost, toprakta organik madde birikimini teşvikler, azot, fosfor, potasyum, kalsiyum, magnezyum ve sodyum gibi temel besin elementlerinin mevcudiyetini artırmaktadır. Bu durum, bitki beslenmesini ve büyümesini desteklemenin yanında, fotosentez kapasitesini ve yaprakların klorofil içeriğini de olumlu yönde etkilemektedir. Ayrıca vermikompost, toprak pH'ını dengeleyerek elektriksel iletkenliği iyileştirir ve tuzluluk sorununa yol açmadan bitki gelişimini desteklemektedir. Solucanların toprağı fiziksel olarak işleyerek sıkışıklığı azaltmaları, suyun toprak profiline nüfuz etmesini önemli ölçüde artırmaktadır. Tüm bu özellikler göz önüne alındığında, vermikompost çevresel sürdürülebilirlik ve ekonomik tarım uygulamaları açısından önemli bir organik gübre alternatifi olarak değerlendirilir.

Anahtar Kelimeler: Vermikompost, Organik Madde, Besin Elementi.

NUTRIENT COMPOSITION OF VERMICOMPOST

ABSTRACT

Vermicompost application is the process of converting plant- and animal-based organic wastes into a stable, nutrient-rich organic fertilizer called vermicompost with the help of earthworms and beneficial microorganisms. This biological fertilizer improves soil structure by increasing porosity and water-holding capacity, while also regulating air circulation. Vermicompost promotes the accumulation of organic matter in the soil and enhances the availability of essential nutrients such as nitrogen, phosphorus, potassium, calcium, magnesium and sodium. This not only supports plant nutrition and growth but also positively affects photosynthetic capacity and the chlorophyll content of leaves. Additionally, vermicompost balances soil pH, improves electrical conductivity, and supports plant development without causing salinity problems. The physical activity of earthworms in the soil reduces compaction and significantly improves water infiltration into the soil profile. Considering all these features, vermicompost is regarded as an important organic fertilizer alternative for environmental sustainability and economically viable agricultural practices.

Keywords: Vermicompost, Organic Matter, Nutrient Element.

1.Giriş

Vermikompostun, hayvansal ve bitkisel atıkların yönetimini daha kolay hale getirdiği ve bu atıkların değerlendirilmesini sağladığı ifade edilmiştir. Ayrıca, vermikompostun besin elementi kayıplarını düşürdüğü, bitki verimliliğini artırdığı, toprakların fiziksel, kimyasal ve biyolojik özelliklerini iyileştirmesi nedeniyle güvenilebilir bir organik gübre olduğu belirtilmiştir. Vermikompostun yeterli miktarda faydalı bitki besin maddeleri içerdiği, toprak düzenleme özelliğine sahip olduğu, bazı pestisit ve bitki hastalıklarını kontrol ettiği ve uzun vadede kullanılması durumunda ekonomik olduğu bildirilmiştir (Bellitürk, 2016). Farklı amaçlar için toprak solucanlarının kültürünün yapılması işlemi vermikültürdür (Edwards ve Bohlen, 1996). Solucanlar uygun düzeyde besin ortamı için %65-75 oranlarında neme ihtiyaç duyarlar ancak bakteriler için optimum nem oranı %55'dir (Rostami ve ark., 2010). Faaliyetleri için optimum sıcaklık 15-25 Co aralığında olup bu sıcaklık derecesi türlere göre farklılık da gösterebilmektedir. Optimum seviyede mikrobiyal faaliyetlerin gerçekleştirilmesi ve devam edebilmesi için aynı zamanda organik maddelerin parçalanma hızının en üst seviyede olması için de en uygun sıcaklık 15-30 Co arasındadır (Rostami vd., 2009). Vermikompost üretimi için seçilen substrat materyalin karbon- azot (C: N) oranı oldukça önemlidir. C: N oranının yüksek olması mikrobiyal faaliyetlerin azalmasına sebep olmaktadır (Ökmen ve Algur, 2000).

2.Vermikompost Nedir

Bitkisel ve hayvansal kökenli organik atıkların, toprak solucanları ve yararlı mikroorganizmalar aracılığıyla biyolojik olarak parçalanarak yapıtaşlarına ayrılması süreci vermikompostlama olarak adlandırılır. Bu süreç sonucunda elde edilen ürün ise vermikompost ya da biyohumus şeklinde tanımlanır. Genellikle *Lumbricus rubellus* ve *Eisenia fetida* gibi solucan türlerinin kullanıldığı bu yöntemle, organik atıklar değerlendirilerek çevre dostu bir gübre üretilir. Atıkların bu şekilde geri dönüştürülmesi, çevresel sürdürülebilirlik açısından önemli katkılar sunmaktadır (Demir, 2010).

Vermikompost toprakların strüktür yapısını düzenleyerek gözenek yapısını iyileştirir, su tutma kapasitesini artırır ve hava ekonomisini düzenlemektedir (Bellitürk, 2016).

Toprak ekosisteminde kritik bir rol oynayan toprak solucanları, toprak verimliliğini artırmada önemli katkılar sağlar. Yapılan araştırmalar, bu canlıların toprak üzerindeki etkilerinin fiziksel, kimyasal ve biyolojik mekanizmalarla gerçekleştiğini ortaya koymuştur (Dindar, 2008).

Kompost üretiminde kullanılacak solucanların, organik maddeleri hızla ve etkili bir şekilde parçalama yeteneğine sahip olmaları gerekmektedir. Toprağın doğal yapısında sıkça rastlanan solucanlar, kompost yapımında kullanılan türler değildir. Kırmızı kompost solucanları, organik maddeleri hızlı bir şekilde öğütüp parçalama konusunda son derece etkilidir. En yaygın kullanılan bu türler arasında *Eisenia fetida* ve *Lumbricus rubellus* yer alır. Bu solucanlar ticari olarak temin edilebileceği gibi, hayvancılık alanlarında, gübre yığınlarında, çöplüklerde ve organik maddelerce zengin topraklarda da bolca bulunabilirler (Domínguez ve Edwards, 2011).

3. Vermikompostun Toprak Organik Maddesi Üzerindeki Etkisi

Geleneksel tarım uygulamaları, toprak ve su kaynaklarının giderek daha fazla kirlenmesine yol açmaktadır. Bu durum, kimyasal gübrelerin yerine organik gübrelerin kullanılmasının giderek daha fazla tercih edilmesine neden olmuştur (İlay ve ark., 2013).

Vermikompost, özellikle toprakta organik madde miktarını artırarak, kimyasal gübrelerin kullanımını ortadan kaldırarak üreticilere ekonomik fayda sağlamakta ve toprak sürdürülebilirliğini destekleyerek sağlıklı bitki üretimini teşvik etmektedir; bu faydalar birçok araştırmacı tarafından vurgulanmıştır (Aksu ve ark., 2017).

Vermikompost uygulamasının yapıldığı çalışmalarda ise vermikompostun toprağın organik madde içeriğini arttırdığı vurgulanmaktadır (Tavalı ve ark., 2014; Çıtak ve ark., 2014).

Vermikompost, su tutma kapasitesini artırarak, toprak pH'sını ve organik madde miktarını iyileştirip mikrobiyal aktiviteyi teşvik ederek hem ürün verimliliği hem de toprak sağlığı üzerinde önemli olumlu etkiler yaratmaktadır (Chan ve ark., 2008; Steiner ve ark., 2007; Dias ve ark., 2010).

4. Vermikompostun Toprak Özelliklerine Etkisi

Bir çalışmada, farklı miktarlarda topraklara uygulanan vermikompostun, en yüksek doz olan 15 t ha-1'de, toprakların toplam organik karbon, toplam azot, fosfor, potasyum, kalsiyum, çinko ve mangan içeriklerinde kontrol grubuna göre anlamlı artışlar sağladığı tespit edilmiştir. Ayrıca, uygulanan vermikompostun toprakların elektriksel iletkenlik (EC) değerini artırdığı, toprak pH'sını ise düşürdüğü belirlenmiştir. Toprak fiziksel özellikleri açısından ise hacim ağırlığı ve toplam porozite gibi değerlerin vermikompost uygulaması ile iyileştiği gözlemlenmiştir (Azarmi ve ark., 2008).

Bir sera deneyinde, topraklara farklı miktarlarda (0, 250, 500, 750, 1000 kg da-1) vermikompost uygulamasının yalnızca toprak kireci üzerinde etkili olduğunu, diğer toprak özelliklerinde ise herhangi bir değişiklik meydana getirmediğini tespit etmişlerdir (Köksal ve ark., 2017).

Organik bir gübre olan vermikompostun farklı dozlarının bitki ve toprak özellikleri üzerindeki etkilerini incelemişlerdir. Araştırmada, toprak reaksiyonu, suda çözünebilen tuz miktarı, kireç, organik madde, fosfor ve potasyum gibi toprak özellikleri değerlendirilmiştir. Toprak özelliklerinden toprak reaksiyonu ile fosfor değerleri arasındaki farklar istatistiksel olarak anlamlı bulunurken, vermikompost uygulamalarıyla suda çözünebilen tuz, kireç ve organik madde miktarlarında değişiklikler gözlemlenmiş, ancak bu değişiklikler istatistiksel olarak anlamlı bulunmamıştır (Özkan ve ark., 2016).

Farklı kombinasyonlarda beş farklı biyo-gübrenin, killi tın yapısındaki bir toprağa uygulanarak agregat oluşumu üzerindeki etkilerini incelemişlerdir. 90 gün süren inkübasyon sonrası, alg ve vermikompost uygulamalarının, 2–1 mm boyutundaki agregatların miktarını kontrol grubuna göre anlamlı şekilde artırdığı belirlenmiştir. Ayrıca, vermikompost uygulamasının 4 mm'den büyük agregatların miktarında da önemli artışlar sağladığı gözlemlenmiştir (Sönmez ve Yılmaz, 2016).

5. Vermikompostun Topraktaki Makro Bitki Besin Elementleri Üzerindeki Etkisi Nedir?

Vermikompost uygulaması toprak organik maddesi, toplam N, P, K, Na, Ca ve Mg konsantrasyonlarını artırır (Nascimento ve ark., 2004) ve toprak yapısını ve bitki beslenmesini, büyümesini, fotosentezini ve yaprakların klorofil içeriğini iyileştirir Fernández-Luqueño ve ark., (2010); Rekha ve ark., (2018), bu da bitki gelişimini olumlu etkiler. Verminkompost tüm besinleri kolayca erişilebilir formda sağlar ve bitkiler tarafından besin alımını artırır. Toprakta kullanılabilir azot, vermikompost seviyelerinin artmasıyla önemli ölçüde arttı ve en yüksek azot alımı elde edilir. Vermikompost ortalama %1,5- %2,2 N, %1,8-%2,2 P ve %1,0-%1,5 K içerir (Adhikary, 2012).

Her gün organik maddeler (mikrop, bitki ve hayvan artıkları) içeren büyük miktarda toprağı yutarlar, bunları midelerinde öğütürler ve enzimlerin yardımıyla bağırsaklarında sindirirler. Kimyasal olarak sindirilen ve yutulan materyalin sadece %5-%10'u vücuda emilir ve geri kalanı, NKP (nitratlar, fosfatlar ve potasyum), mikro besinler ve faydalı toprak mikropları açısından zengin olan "vermicasting" adı verilen ince mukus kaplı granüler agregalar şeklinde atılır (Adhikary, 2012).

Vermikompost uygulaması ayrıca besin döngüsünde, bitki büyüme düzenleyicilerinin üretiminde ve bitki büyümesini teşvik eden humik maddelerin üretiminde önemli bileşenler olan mikrobiyal biyokütleyi, çeşitliliği ve mikrobiyal aktiviteyi artırarak toprağın kalitesini de iyileştirir ve bu da zararlı istilasını önemli ölçüde bastırmaya yardımcı olur (Arancon ve Edwards, 2005; Edwards ve ark., 2004; Rostami ve ark., 2014).

Topraktaki bazı mikroorganizmalar bitki rizosferlerinde sinerjik ilişkiler kurar ve böylece bitkilerin toprak nemini ve besin maddelerini, antibiyotikler ve hastalık antagonistleri gibi bazı mikrobiyal yan ürünleri kullanma kapasitesini artırmaya yardımcı olur (Arancon ve Edwards, 2005).

Solucan kompostu nitratlar, fosfatlar, çözünebilir potasyum ve magnezyum ile değiştirilebilir fosfor ve kalsiyum içerirler, haşere kompostunun, bitkiler optimum beslenmeye tabi tutulduğunda bile bitki büyümesini teşvik ettiği ortaya koyulmuştur. Vermikompostun bitki büyümesi üzerindeki doğrudan etkilere gelince, vermikompost bir P kaynağı oluşturur. Makro ve mikro besinlerin bir kısmı inorganik olarak mevcuttur ve bitkiler tarafından kolayca elde edilebilirler, çoğu kademeli olarak salınır ve mineralizasyon yoluyla organik madde oluşturulur. Bitkiye besin sağlayan yavaş salınımlı bir gübre kademeli ve sürekli şekilde besin kaynağı olmaktadır. Ancak kimyasalın aksine gübrelerde sağlanan besin miktarı orijinaline bağlı olarak büyük ölçüde değişebilir. Bitki saksı ortamına vermikompost ve makro besin elementi eklenmesi önemli bir değişikliğe neden olur fiziksel olarak etkide bulunur. Suyu değiştirmeve substratlarda hava bulunabilirliğini sağlamaya ve kök gelişimini düzenlemeye yardımcı olur (Chaoui ve ark., 2003).

6. Vermikompostun Topraktaki Mikro Bitki Besin Elementleri Üzerindeki Etkisi

Kıvırcık salata (*Lactuca sativa* var. crispa), yüksek su içeriği ve sığ kök yapısı nedeniyle kuraklık stresine karşı duyarlı olan bir sebze türüdür. Kurak koşullarda yetiştirilen bitkilerde gelişim yavaşlar, verim ve kalite kayıpları gözlemlenir. Bu nedenle, stresin olumsuz etkilerini hafifletmede vermikompost önemli bir çözüm olabilir. Bellitürk ve ark., (2017) tarafından yapılan bir çalışmada, kıvırcık salataya vermikompost ve farklı organik gübrelerin etkisi incelenmiş ve vermikompost uygulaması ile bitkinin potasyum ve çinko içerikleri arasında negatif bir korelasyon bulunmuştur. Bu araştırmada, vermikompostun kuraklık stresinin kıvırcık salata üzerindeki olumsuz etkilerini azaltmadaki rolü ve bitkinin kuraklığa dayanıklılığını desteklemedeki işlevi tartışılmıştır.

Demir, klorofil, fotosentez, solunum ve enzim sistemlerinin oluşumunda önemli bir role sahip olmaktadır ve bitkilerde oksidatif stres ile önemli ölçüde azalmaktadır (Havlin ve ark., 1999; Sivritepe ve ark., 2008; Kostopoulou ve ark., 2015).

Mangan, demir ile birlikte klorofil üretimini destekleyen ve fotosentez için gerekli olan bir elementtir. Ayrıca, kuraklık stresi sırasında oluşan serbest radikallerin zararlı etkilerini engellemek amacıyla süperoksit dismutaz enzimini aktive eder (Hebbem ve ark., 2009).

Mn ve Fe' in, nemli toprak koşullarında çözünür formlara dönüşümü ve bitki tarafından alınabilirliği daha kolaydır (Havlin ve ark., 1999).

Çinko, bitkilerde karbonhidrat metabolizması, protein sentezi, oksin metabolizması ve enzim aktivasyonunda önemli bir rol oynarken, bakır çeşitli enzimlerin kofaktörü ve proteinlerin düzenleyicisi olarak işlev görmektedir (Marschner, 1995).

7. Vermikompostun Topraktaki Mikrobiyal Aktivite Üzerindeki Etkisi Nedir

Vermikompostlama, solucanlar ve ilişkili mikropları içeren termofilik olmayan, boioksidatif bir işlem olarak bilinmektedir. Bu biyolojik organik atık ayrıştırma işlemi, biyogübreyi yani

vermikompostu üretir. Vermikompost, yüksek gözenekliliğe, iyi havalandırmaya, drenaja, su tutma kapasitesine, mikrobiyal aktiviteye, mükemmel besin durumuna ve tamponlama kapasitesine sahip ince bölünmüş, turba benzeri bir malzemedir ve böylece toprak verimliliği ve bitki büyümesi için uygun olan gerekli fizikokimyasal karakterlerin elde edilmesine yardımcı olur. Vermikompost, yararlı mikropları teşvik ederek toprak biyoçeşitliliğini artırır ve bu da bitki büyümesini doğrudan bitki büyümesini düzenleyen hormonlar ve enzimler üreterek ve dolaylı olarak bitki patojenlerini, nematodları ve diğer zararlıları kontrol ederek artırmış olur, böylece bitki sağlığını iyileştirir ve verim kaybını en aza indirir. Doğal biyolojik, biyokimyasal ve fizikokimyasal özellikleri nedeniyle vermikompost, sürdürülebilir tarımı teşvik etmek ve ayrıca aksi takdirde yaşam ve çevre için ciddi tehdit oluşturabilecek tarımsal, endüstriyel, evsel ve hastane atıklarının güvenli yönetimi için kullanılabilir (Pathma, 2012).

8. Vermikompostun Topraktaki Bazı Enzim ve Bitki Büyüme Hormonları Üzerindeki Etkisi

Vermikest, piyasada mevcut olan tüm organik gübreler arasında en yüksek verime sahip olanıdır. Vermikestin mikrobiyal aktivite seviyesi, toprağa göre 10 ila 20 kat daha fazladır. Bu yüksek mikrobiyal çeşitlilik, bitki gelişimini destekleyen kimyasallar (hormonlar ve diğer bileşikler) ile zararlı bitki patojenlerinin büyümesini engelleyen enzim ve çeşitli bileşiklerin üretimini sağlar (Logsdon, 1994).

Vermikestin içinde bulunan, solucan mukusu ile sarılmış besin elementleri, yavaş bir şekilde salınarak bitkiler tarafından hemen kullanılabilir formda bulunur. Bu besinler yavaşça çözüldüğünden, sızıntı yoluyla besin kaybı yaşanmaz. Ayrıca, vermikestin yüksek gözenek yapısı, su tutma kapasitesi ve iyi havalanması sayesinde mükemmel bir toprak düzenleyici görevi görür. Bu özelliklerin yanı sıra, materyal bitki köklerini aşırı sıcaklıklardan korur, erozyonu önler ve yabani otların gelişimini engeller. Vermikest, hem sera hem de saksı toprakları için ideal bir karışım maddesidir. Bahçe ve tarla bitkilerinde bu olumlu etkiler gözlemlenmiştir. Hatta en hassas bitkilerde bile yanma etkisi görülmez ve tüm besin elementleri suda çözünebilen özellik taşır. Malç olarak kullanıldığında, sulama ile besin elementleri doğrudan bitki köklerine ulaşır (Anonim, 1992).

Vermikestin bitki besleme üzerindeki etkisi, ilk kez Fosgate ve Babb, (1972) tarafından bildirilmiştir. Araştırmada, sığır gübresinden elde edilen kestinin, "özel sera çiçek karışımına" denk seviyelerde bitki büyümesini teşvik ettiği belirtilmiştir.

Handreck (1986), vermikestin bitkilerin çoğu iz element ihtiyacını karşılayabileceğini ancak çoğu kestinin bitkilerin tüm azot gereksinimini karşılayamayacağını belirtirken; Edwards ve ark. (1985), organik atıkların çoğunda yeterli besin bulunduğunu ve vermikompost sürecinde azot kaybının oldukça düşük olduğunu savunmaktadır.

9. Solucan Gübresi Kullanılarak Zararlı Yönetimi

Böcekler, poikilotermik yani değişken vücut sıcaklığına sahip organizmalar oldukları için, fizyolojik özellikleri çevresel hava koşulları ve iklimdeki değişimlere karşı son derece duyarlıdır (Kocmankova ve ark., 2009).

Artan bilimsel veriler, iklim değişikliğinin zararlı organizmaların popülasyon dinamiklerini, büyüme, denge, tür bileşimi ve mekânsal ve zamansal dağılımlar açısından nasıl etkilediğini ortaya koymaktadır. Örneğin, sıcak ve kuru koşullardan hoşlanan (termo- ve kserofilik) zararlılar, iklim değişiklikleri nedeniyle yerel olarak popülasyon artışını desteklerken, soğuk iklimleri tercih eden (psikrofilik) zararlılar üzerinde olumsuz etkiler oluşturabilir. Ayrıca, bazı bölgelerde yabancı ve göçmen zararlı türlerinin popülasyon artışı beklenmektedir (Skendzic ve ark., 2021). Küresel ısınmanın etkisiyle iklimdeki değişiklikler devam ettikçe, bitki parazitleri

ve hastalıklarının tarım alanlarındaki etkisi artacaktır. Vermikompost ve benzeri ürünler, değişen iklim koşullarından kaynaklanan potansiyel ürün kayıplarını azaltmak için yardımcı olabilecek doğal çözümler sunmaktadır (Coopoosamy ve ark., 2023).

9.1. Nematodlar

M. Renco ve ark. (2015), farklı dozlarda uygulanan vermikompostun katı ve sıvı özütlerinin patates kist nematodları (Globodera rostochiensis ve G. pallida) üzerindeki etkilerini incelemişlerdir. Uygulama miktarları arttıkça, toprakta 400 g başına düşen kist, yumurta ve ikinci evre larva sayılarında belirgin azalmalar gözlemlenmiştir. Ayrıca, sıvı VCL'nin katı vermikomposta göre nematodları kontrol etmede daha etkili olduğu ve bu etkinin üre eklenmesiyle daha da arttığı belirlenmiştir.

9.2. Eklem Bacaklılar

Arancon ve ark. (2007) tarafından yapılan bir çalışmada, vermikompostun bazı bahçe bitkilerinde artropod zararlıların popülasyon artışını baskılama ve zararını azaltma etkileri değerlendirilmiştir. Araştırmacılar, vermikompost uygulamalarının bitki dokularında fenol birikimine yol açtığını, bunun da bitkileri zararlılar için tatsız hale getirdiğini öne sürmüşlerdir.

Giderek artan sayıda bilimsel çalışma, organik gübre uygulanan bitkilerin, kimyasal gübrelerle beslenen bitkilere kıyasla artropod zararlılara karşı daha dayanıklı olduğunu ortaya koymaktadır. Bazı bilim insanları, sentetik azotun bitkilerde fenolik bileşikler ve diğer doğal savunma maddelerinin sentezini engelleyebileceğini ileri sürmektedir. Ayrıca, bu tür azotlu gübreler bitkilerin besin içeriğini ve tat profilini geliştirerek zararlılar için daha çekici hale getirebilir. Öte yandan, organik gübrelerin besin elementlerini yavaş salmaları nedeniyle bu maddelerle yetiştirilen bitkilerde azot ve diğer besin maddeleri daha düşük düzeyde bulunmakta, bu da bitkilerin zararlılara karşı savunmasını güçlendirebilmektedir (Fragoyiannis ve ark. 2021; Herms ve ark., 2002).

10. Vermikompostun Diğer Yararları Nelerdir?

Vermikompost uygulamaları, toprağı mikro ve makro besin maddeleri, vitaminler, enzimler ve hormonlarla zenginleştirmekle birlikte fizikokimyasal özellikleri düzenleyerek bitki gelişimine katkı sağlamaktadır (Makulec, 2002) (Sinha ve ark., 2009; Hazra, 2016).

Vermikompost ürünleri, bitkilerin doğrudan alabileceği formda temel besin maddeleri içermektedir (Pathma ve Sakthivel, 2012; Lim ve ark., 2012). Bunun temel nedeni, termolitik kompostlamadan sonra vermikompostun, daha fazla çözünmenin gerçekleştiği mezolitik kompostlama sürecinden geçmesidir. Vermikompost, humik asitler açısından zengin belli bir materyale dönüşerek bitki biyokütlesinin ve kök gelişiminin artmasına katkıda bulunmaktadır (Delibacak ve Ongun, 2016; Erdal ve ark., 2000; Sönmez ve ark., 2013).

Toprakta bulunan bitki besin elementleri, çeşitli faktörler tarafından tutulabilir veya zıt iyonlarla bileşikler oluşturur. Vermikompost, sadece bitki büyümesini desteklemekle kalmayıp, bununla birlikte toprak pH'ını düzenler ve tuzluluk problemi oluşturmadan elektriksel iletkenliği artırmaya yardımcı olur (Argüello ve ark., 2006).

Vermikompost uygulaması, topraktaki su-hava dengesini iyileştirir ve makro gözeneklilik oranını 50 mikrometreden 500 mikrometreye çıkarmaktadır (Marinari ve ark., 2000).

Vermikompostun yüzey alanı, mikro gözenekli alanı artırır ve bu sayede daha fazla besin maddesinin tutulmasına olanak tanır (Shi-wei ve Fu-zhen, 1991; Ali ve ark., 2015).

Vermikompost ile birlikte toprağa uygulanan daha fazla inorganik N, P, K gübresinin bitkiler tarafından alındığı bildirilmiştir (Thirinavukkarasu ve Vinoth, 2013). Ayrıca, vermikompost

uygulamalarının, bozulmuş tropikal topraklarda, termolitik kompost ve inorganik N, P, K gübrelerine kıyasla bitki büyümesi ve toprak yapısı üzerinde daha olumlu etkisinin olduğu da belirlenmiştir (Jouquet ve ark., 2011).

Kırmızı solucan döküntüleri yüksek oranda humus içerir. Humus, toprak parçacıklarının kümeler halinde oluşmasına yardımcı olur, bu da havanın geçişi için kanallar oluşturur ve su tutma kapasitesini artırır. Solucanların varlığı sıkıştırılmış toprağı yeniler ve bu tür topraklardaki su penetrasyonunu %50'nin üzerinde artırır.

Humusta bulunan humik asit, kalsiyum, demir, potasyum, kükürt ve fosfor gibi bitki besinleri için bağlanma yerleri sağlar. Bu besinler, humik asitte bitkilerin kolayca alabileceği bir biçimde depolanır ve bitkilerin ihtiyaç duyduğu zaman salınır. Solucan gübresindeki "hümik asit", az miktarda bile olsa bitki büyümesini uyarır. Solucan bağırsağının aktivitesi, koşulları karıştıran ve kalıntıları aşılayan minyatür bir kompost tüpü gibidir. Bağırsaktaki nem, pH ve mikrobiyal popülasyonlar, sinerjik bir ilişki ve ardından harika bir yan ürün için uygun şekilde korunur (Adhikary, 2012).

11. Sonuç ve Öneriler

Vermikompostun bitki besin maddesi içeriği, toprak sağlığına katkısı ve mikrobiyal aktivite üzerindeki olumlu etkileri sürdürülebilir tarım sisteminde oldukça önemlidir. Vermikompostun kullanımı, toprakta organik madde birikimini destekleyerek yapısal özellikleri iyileştirir, su tutma kapasitesini artırır ve mikrobiyal çeşitliliği zenginleştirmektedir. Ayrıca, kimyasal gübre kullanımının azaltılmasını sağlayarak çevresel kirliliği azaltmakta ve ekosistemi desteklemektedir.

Sürdürülebilir tarım hedeflerine ulaşılması için vermikompost kullanımının yaygınlaşması önemlidir. Tarımsal üretimde organik atıkların değerlendirilmesini teşvik eden politikaların geliştirilmesi, çiftçilere yönelik eğitim programlarının uygulanması gerekmektedir.

Gelecekte yapılacak araştırmalarda, vermikompostun verimlilik, toprak kalitesi ve çevresel etki konularında yararları ve kullanımının ayrıntılı olarak değerlendirilmesi daha iyi bir tarım için faydalı olacaktır.

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BREEDING AND QUALITY IMPROVEMENT STRATEGIES FOR PLANT PROTEIN DEMAND IN LEGUMES: MODERN APPROACHES AND FUTURE PERSPECTIVES

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ABSTRACT

The growing global demand for plant-based protein underscores the strategic importance of legumes in developing sustainable food systems. Legumes are a valuable resource for the nutrition and functional food industries, not only for their high protein content but also for their amino acid composition, fiber, and bioactive compound richness. This study evaluated modern breeding approaches to increase the quantity and quality of protein in legumes. The effective use of genetic variation, marker-assisted selection (MAS), genomic selection (GS), pangenome analyses, high-throughput phenotyping (HTP), and the integration of advanced bioinformatics tools is critical for developing high-protein, highly processable lines. Furthermore, the development of protein fractions, reduction of anti-nutritional factors, improvement of digestibility, and the effects of environment × genotype interactions on quality parameters were discussed. The development of new legume varieties tailored to the needs of the functional food, plant-based meat, and alternative protein industries will be one of the main directions of breeding programs in the future. This review highlights the opportunities provided by modern breeding techniques and future research priorities, emphasizing the role of legumes in closing the global protein gap.

Keywords: Legumes, Plant Protein, Breeding Strategies, Protein Quality, Genomic Selection

1. Introduction

The increase in global population, the pressure of climate change on agricultural production, and the search for sustainable diets have markedly heightened the demand for plant-based protein sources in recent years. According to FAO (2023) projections, protein demand is expected to rise by at least 50% by 2050, and a substantial proportion of this requirement will need to be met from environmentally more sustainable sources. Grain legumes, with their high protein contents (20–35%), essential amino acid profiles, low carbon footprints, and symbiotic nitrogen fixation that enhances soil fertility, occupy a strategic position among the "protein crops of the future" (Foyer et al., 2019). In this respect, legumes are critical to both human nutrition and sustainable agricultural production systems.

However, the growing consumer demand necessitates not only the development of high-yielding genotypes but also the improvement of protein quality parameters, including essential amino acid balance, digestibility, levels of antinutritional factors, and functional food properties. Contemporary consumer trends are rapidly increasing the demand for high-quality protein fractions with superior gelling, solubility, viscosity, and emulsifying properties in processed products such as legume-based meat analogues, dairy alternatives, and functional foods (Boye et al., 2010; Lam et al., 2018). Therefore, breeding programs need to develop multidimensional strategies that focus not only on yield and adaptation traits but also on protein functionality and processing-related quality parameters.

Today, classical breeding methods are rapidly being transformed through integration with genomic selection, marker-assisted selection (MAS), high-throughput phenotyping, multi-omics platforms (transcriptomics, proteomics, metabolomics), CRISPR/Cas-based genome editing, and artificial intelligence-supported data analytics. More efficient use of genetic variation is becoming possible particularly through the incorporation of wild relatives and local genotypes into breeding programs in major legume genera such as *Pisum*, *Cicer*, *Vigna* and *Phaseolus* (Smýkal et al., 2015). In addition, in the context of climate change, increasing heat, drought, salinity and disease stresses directly affect both protein synthesis and quality components, thereby highlighting the necessity of new-generation breeding strategies that jointly optimize stress tolerance and quality traits.

This section aims to comprehensively discuss, in the light of current literature, modern breeding approaches, quality improvement strategies, and future research perspectives developed in response to the increasing demand for plant-based protein in legumes.

2. Protein Composition and Nutritional Value in Legumes

Legume seeds generally contain 18–35% protein on a dry matter basis, and most of this protein is composed of storage proteins belonging to the globulin and albumin fractions. In various legume species, globulins account for approximately 35–80% of total seed protein, whereas albumins constitute 2–37% (Singh et al., 2022). This biochemical structure makes legumes an important plant-based protein source for both human nutrition and industrial applications.

2.1. Protein Content and Fractions (Globulin, Albumin, etc.)

Legume seed proteins are classified according to the classical Osborne fractionation system into albumins (water-soluble), globulins (salt-soluble), prolamins (alcohol-soluble), and glutelins (acidic/basic soluble) (Carbonaro & Nucara, 2022). The predominant storage proteins in legumes are globulins, especially the 7S vicilin and 11S legumin subunits, which may represent up to 90% of total globulins in some species (Ohanrnye et al., 2022). The albumin fraction, on the other hand, contains biologically active proteins, such as enzymes, protease and amylase

inhibitors, and lectins, which play a central role in seed defense mechanisms (Singh et al., 2022).

Significant variation exists among species and within species for their globulin/albumin ratios, indicating that not only total protein content but also fractional composition can be targeted in breeding programs. A higher globulin ratio is associated with improved gelling and emulsifying properties valued in the food industry, whereas reducing the albumin fraction may help lower antinutritional activity in certain legume species (Boye et al., 2010).

2.2. Amino Acid Profile and Nutritional Quality

Legume proteins are typically rich in lysine but limited in sulfur-containing amino acids such as methionine and cysteine (Hertzler et al., 2020). Recent studies indicate that sulfur amino acids represent the primary limiting amino acids in species such as pea (Sá et al., 2024). Conversely, cereals are often deficient in lysine; thus, legume–cereal combinations significantly improve overall dietary protein quality, increasing PDCAAS and DIAAS scores due to complementary amino acid profiles (Pulse Canada, 2025).

There is considerable variation among genotypes and species in amino acid composition, with certain genotypes exhibiting more balanced essential amino acid profiles (Bessada et al., 2019). This provides opportunities for classical breeding and genomic selection efforts to target traits such as high lysine content, improved sulfur amino acid levels, and better essential amino acid balance.

2.3. Antinutritional Factors and Functional Components

In addition to their high protein and mineral contents, legumes contain several antinutritional factors (ANFs). The major ANFs include protease inhibitors (especially trypsin inhibitors), amylase inhibitors, lectins, phytic acid, tannins, saponins, and various polyphenolic compounds (Samtiya et al., 2020). These compounds can reduce protein and mineral bioavailability by forming complexes with nutrients or by inhibiting digestive enzymes, particularly phytic acid and tannins, thereby limiting digestibility (Gilani et al., 2012).

On the other hand, bioactive peptides derived from legume proteins exhibit antioxidant, ACE-inhibitory, antidiabetic, and antimicrobial properties, highlighting legumes as a valuable source of health-promoting bioactive compounds (Carbonaro & Nucara, 2022).

2.4. Protein Digestibility and Processing Properties

Protein digestibility in legumes is generally lower than in animal proteins and certain processed soy products. This reduced digestibility stems primarily from the presence of ANFs, protein–polysaccharide complexes, and the seed matrix's structural characteristics. Elevated levels of tannins and phytic acid have been associated with reductions of 10–23% in protein and amino acid digestibility (Gilani et al., 2012).

These functional characteristics directly influence the suitability of legume proteins for various food applications, particularly plant-based meat analogues, dairy alternatives, bakery products, and snacks. Therefore, breeding programs must consider not only crude protein concentration but also digestibility, functional traits, and processing performance. Integrating these criteria is essential for developing future quality-oriented legume varieties (Bessada et al., 2019).

3. Genetic Resources and Variation in Protein Quality

In legume species, the wide variation observed in seed protein content, amino acid composition, and levels of antinutritional compounds largely depends on the quality of the genetic resources utilized and the extent to which these resources are integrated into breeding programs.

Vavilov's concept of centers of origin highlights that regions such as the Mediterranean Basin, West Asia, Ethiopia, and South Asia harbor rich reservoirs of protein-related genetic diversity through local landraces and wild relatives (Smýkal et al., 2015). Recent advances in genome sequencing, pangenomics, and multi-omics approaches have revealed that this variation exists not only at the morphological or agronomic level but also at the genomic scale, including differences in **core–accessory genome organization, presence–absence variation (PAV)**, and large-scale structural variation (Ruperao et al., 2025).

Within this framework, genetic diversity analyses conducted on wild relatives, landraces, and modern cultivars collected from these gene centers play a critical role in identifying allele and gene combinations associated with target traits such as high protein content, balanced essential amino acid profiles, and reduced antinutritional factor levels (Jha et al., 2022).

3.1. Centers of Origin, Wild Relatives, and Landraces

The primary and secondary centers of diversity identified in Vavilov's classical work represent significant reservoirs of variation for both adaptive traits and seed quality parameters in legumes. The Mediterranean region, West and Central Asia, and Ethiopia stand out as hotspots where both high-protein landraces and drought-, cold-, and disease-tolerant wild forms of pea, chickpea, and lentil are concentrated (Smýkal et al., 2015; Dueholm et al., 2025). Genetic materials stored in FAO and national gene bank collections often contain alleles that have been lost in modern cultivars and therefore serve as strategic resources for breeding.

Wild relatives, such as *Cicer reticulatum* and *C. echinospermum* for chickpea, and *Pisum fulvum* and *P. abyssinicum* for pea, and traditional landraces generally exhibit **higher crude protein content, distinct storage protein profiles**, and **enhanced micronutrient–protein associations** (e.g., Fe–Zn–protein), while often performing lower than elite cultivars in yield and harvest index (Smýkal et al., 2015; Jha et al., 2022). Consequently, breeding strategies incorporating materials from gene centers must prioritize optimizing high protein content alongside stable yield performance while actively managing genotype × environment (G×E) interactions.

Landraces, shaped through farmer selection over long periods, are typically adapted to specific local environments and often possess unique grain quality traits (color, flavor, cooking time) as well as niche properties related to protein quality and utilization (Dueholm et al., 2025). In modern breeding programs, crossing these landraces with high-yielding elite lines provides a vital bridge to conserve quality alleles while simultaneously improving productivity.

3.2. Genetic Diversity Analyses and Omics-Based Characterization

Effective use of protein-quality-related variation in legumes requires a multilayered characterization strategy that goes beyond classical morpho-agronomic evaluation and integrates molecular and omics-based tools. Traditional molecular markers such as SSRs and AFLPs, along with high-density SNP panels and genotyping-by-sequencing (GBS) platforms, are widely used to dissect genetic structure, population stratification, and phylogenetic relationships in chickpea, lentil, pea, and cowpea (Jha et al., 2022).

More recently, whole-genome sequencing (WGS), resequencing panels, genome-wide association studies (GWAS), and genomic selection approaches have been applied to elucidate the genetic basis of complex quality traits, including **seed protein concentration, essential amino acid composition** (e.g., lysine, methionine), and **mineral–protein relationships** (Fe, Zn) (Wohor et al., 2025). The identification of multilocus, small-effect QTLs and candidate genes involved in protein biosynthesis and storage pathways enables the systematic

incorporation of quality parameters into MAS and GS pipelines (Jha et al., 2022; Cordoba et al., 2025).

Complementary omics datasets, including transcriptomics, proteomics, and metabolomics, provide deeper insights into protein accumulation during grain filling, isoform profiles of storage proteins, and interactions between antioxidant/secondary metabolites and protein composition (Ali et al., 2022; Cummane et al., 2025).

Integrating these multi-omics datasets with pangenomic and classical genetic diversity analyses facilitates the development of novel selection indices that simultaneously target **high protein content, enhanced quality**, and **environmental stress tolerance**. As a result, wild relatives and landraces from gene centers are transformed from mere sources of diversity into **strategic donor materials** whose allelic variation is fully characterized at the omics level and can be directly utilized to improve protein quality in breeding programs.

4. Classical Breeding Strategies for Increasing Protein Content

Classical breeding efforts aimed at improving seed protein content in legumes fundamentally rely on exploiting existing genetic variation (landraces, wild relatives, elite lines) through appropriate selection methods, followed by the stabilization of high-protein genotypes without sacrificing yield and adaptation performance. In traditional programs, protein concentration often shows a negative correlation with seed yield, making single-trait selection insufficient and necessitating the use of selection indices, stepwise selection, and multi-environment testing (Ranalli & Cubero, 1997). In recent years, integrating these classical strategies with genomic selection, marker-assisted selection, and omics datasets has accelerated genetic gains in protein improvement, while allowing a more rational management of the **quality × yield × adaptation** balance (Jha et al., 2022).

4.1. Selection Methods

The first step in classical breeding programs targeting increased protein content is making selection decisions within segregating populations. **Mass selection** and **individual plant selection** have been frequently used to isolate high-protein individuals, particularly from landraces and wild relatives. However, because protein concentration is sensitive to environmental variation and laboratory analyses are costly, these methods are often combined with **laboratory-assisted, stepwise selection** using chemical or NIR-based measurements (Ranalli & Cubero, 1997).

Pedigree selection and **family (progeny) selection** are preferred for quantitative traits such as protein content, especially during the F_2–F_5 generations, as they allow decisions to be based on family means. Protein content generally exhibits moderate heritability, shows a negative correlation with yield, and shows positive associations with seed size and some quality traits. Therefore, combining family means with correlation structures results in more effective selection decisions (Jermyn, 1977; Obala et al., 2022).

The negative correlation between protein concentration and yield necessitates the use of **selection indices**. Smith–Hazel type or **restricted indices** assign positive weights to protein and moderate weights to yield, enabling progressive improvement of protein content without severely reducing yield. Although such indices have been shown to improve yield and protein content in cereals and legumes simultaneously, the rate of genetic gain is often moderate (Michel et al., 2019).

Multi-environment trials (METs) are essential tools for managing genotype-by-environment (G×E) interactions during protein selection. Studies in lentil and chickpea have shown that

although genotypic differences for protein content are significant, environmental effects and G×E interactions also play major roles. Thus, stability analyses such as AMMI and GGE biplot should be integrated into protein-focused selection schemes (Burstin et al., 2011; Subedi et al., 2020).

4.2. Heterosis, GCA–SCA, and Parental Selection

Although most legumes are self-pollinating, heterosis and combining ability (GCA–SCA) analyses are widely used to identify suitable parental combinations for high protein content. Diallel and line × tester studies conducted in pea, bean, and chickpea have revealed significant general combining ability (GCA) and specific combining ability (SCA) variances not only for seed yield and its components but also for protein content and other seed quality traits (Ceyhan et al., 2014; Sharma et al., 2023; Ceyhan et al., 2025; Dalgıç et al., 2025).

Many studies demonstrate that **additive gene effects** (thus GCA) play a dominant role in determining protein content. In contrast, **non-additive effects** (dominance and epistasis), reflected in SCA, are more influential for seed yield, biological yield, and yield components (Ceyhan et al., 2014; Sharma et al., 2023; Ceyhan et al., 2025; Dalgıç et al., 2025). This indicates that parents with high protein content and favorable GCA values are ideal for developing superior pure lines, while crosses with high SCA are more suitable for F_1 hybrid performance or for expanding segregation in subsequent generations.

Line × tester analyses in pea have identified sure parents with significantly positive GCA effects for seed yield, 100-seed weight, seed protein content, and other quality components. Such parents are considered **"good general combiners"** and serve as essential contributors to elite breeding pools (Ceyhan et al., 2014; Ceyhan et al., 2025; Dalgıç et al., 2025). Furthermore, high heterobeltiosis values for both yield and protein content have been reported in specific parental combinations, demonstrating that some crosses can simultaneously provide high yield and relatively high protein levels, partially breaking the classical negative yield-protein relationship (Ceyhan et al., 2014; Sharma et al., 2023; Ceyhan et al., 2025; Dalgıç et al., 2025).

Thus, parental selection in classical breeding programs is no longer based solely on yield and adaptation traits; instead, **GCA estimates for protein content, amino acid composition, and related quality traits** are increasingly emphasized, enabling the development of parental sets with elite combining ability for protein improvement.

4.3. Achieving the Quality × Yield × Adaptation Balance

One of the major challenges in breeding for higher protein content in legumes is the commonly observed negative correlation between seed yield and protein concentration. Multi-environment trials in pea, lentil, and faba bean frequently report moderate to strong negative correlations (approximately –0.6) between these traits. However, certain genotypes break this "upper-limit trend," combining acceptable or high yield with comparatively high protein concentration (Skovbjerg et al., 2020). These exceptional genotypes serve as key genetic resources for achieving the balance among quality, yield, and adaptation.

Protein quality (especially total protein and amino acid composition) is often indirectly associated with adaptation and stress tolerance. Studies on lentil and pea indicate that under abiotic stresses such as drought and high temperatures, yield decreases substantially, while protein concentration is less affected or even slightly increased. Therefore, **protein yield (kg/ha)** serves as a more holistic selection criterion than protein percentage alone (Lake et al., 2021; Tziouvalekas et al., 2022; Soncin et al., 2025).

Consequently, modern breeding programs evaluate **yield, protein percentage, and protein yield simultaneously**, selecting genotypes that achieve the optimal balance of these traits under target environments.

5. Modern Molecular and Genomic Breeding Approaches

In legumes, complex quality traits such as seed protein concentration, amino acid composition, and antinutritional factor content are governed by numerous small-effect QTLs, genotype × environment interactions, and interconnected physiological processes. Consequently, achieving rapid genetic improvement using classical breeding alone is challenging. Over the last 15–20 years, marker technologies, genomic selection, QTL/GWAS-based candidate gene discovery, CRISPR/Cas-mediated genome editing, and high-throughput phenotyping (HTP) have become central components of modern legume breeding programs (Sab et al., 2020; Jha et al., 2022).

5.1. Marker-Assisted Selection (MAS)

Marker-assisted selection provides substantial gains in speed and accuracy compared with classical selection, especially for traits controlled by a single or a few significant genes or large-effect QTLs (Nair & Rabbani, 2024). Although overall seed protein content in legumes is typically polygenic, several key subcomponents—such as storage proteins (vicilin and legumin subunits), phytate metabolism, antinutritional factors (lectins, trypsin inhibitors), and mineral, protein interactions (Fe, Zn), are associated with major QTLs, enabling practical MAS application (Upadhyaya et al., 2016; Sab et al., 2020).

In recent years, markers associated with Fe–Zn–protein co-concentration, phytate levels, specific storage protein fractions, and biotic/abiotic stress tolerance (which indirectly contribute to protein retention) have been identified in chickpea, lentil, common bean, and pea. These markers are increasingly used for **early-generation selection in F_2–F_4 populations** (Upadhyaya et al., 2016; Sab et al., 2020).

Because biochemical protein analyses are time-consuming and expensive, MAS—when combined with rapid NIR/NIT-based protein estimation, has become even more advantageous. In most breeding programs today, MAS is integrated with classical yield- and adaptation-based selection, forming a dual-selection framework that targets both agronomic performance and quality traits (Jha et al., 2022).

5.2. Genomic Selection (GS)

Genomic selection uses dense, genome-wide marker datasets (e.g., SNP panels, GBS-derived markers) to predict the genetic values of individuals without requiring phenotypic measurements, making it especially suitable for traits influenced by numerous small-effect QTLs (Michel et al., 2019; Berkner et al., 2023). Since seed protein concentration, protein yield, and amino acid composition fall into this category, GS has rapidly gained prominence in legume breeding.

A recent study in pea demonstrated that GS models built using multi-location datasets could **simultaneously predict seed yield, protein content, and protein yield**, with robust accuracies across different genetic backgrounds (training vs. target populations) (Michel et al., 2019; Berkner et al., 2023).

In legumes, GS outperforms classical MAS for complex quality traits by providing higher prediction accuracy for protein content, protein yield, and amino acid balance; reducing reliance on costly multi-environment protein phenotyping; enabling early-generation selection using only genotypic data; and integrating the vast diversity of wild relatives and landraces into prediction models.

Thus, GS, together with MAS and HTP technologies, has become one of the foundational tools in modern protein-oriented **legume breeding** (Jha et al., 2022; Cordoba et al., 2015).

5.3. QTL Mapping and Candidate Gene Analysis

QTL mapping and candidate gene discovery play critical roles in protein-focused breeding by enabling the development of markers for MAS/GS and identifying targets for genome editing. Numerous QTLs have been identified for traits such as seed protein content, Fe and Zn concentration, seed size, and storage protein composition in chickpea, lentil, and pea (Verma et al., 2015; Upadhyaya et al., 2016; Sab et al., 2020).

Studies on lentil have shown that certain QTLs simultaneously influence mineral concentration and total protein levels, indicating the presence of pleiotropic or tightly linked loci of particular relevance to biofortification programs (Upadhyaya et al., 2016; Aldemir et al., 2017). In pea, QTLs associated with seed protein content often co-localize with regions controlling legumin/vicilin ratio and seed size, suggesting shared genetic regulation of protein quality and seed physicochemical traits (Upadhyaya et al., 2016; Aldemir et al., 2017).

Integration of QTL mapping results with **GWAS and pangenome data** enables the identification of more stable, environment-independent QTL regions. Candidate genes located in these stable intervals can be validated using CRISPR/Cas and advanced functional genomics approaches (Sab et al., 2024; Zatybekov et al., 2025).

6. Conclusion and Future Perspectives

Grain legumes hold a strategic position in meeting the growing global demand for plant-based proteins and the need for sustainable agricultural production systems. As highlighted in this review, legumes play a critical role not only due to their high crude protein content but also through their essential amino acid profiles, dietary fiber, and bioactive compound richness, symbiotic nitrogen fixation, and low carbon footprint, contributing simultaneously to human nutrition and ecosystem services. However, fully realizing this potential requires moving beyond traditional yield-centered approaches toward integrated breeding strategies that jointly target protein quantity, protein quality, processability, and stress tolerance.

A key conclusion of this study is the presence of extensive genetic variation in protein content, amino acid balance, and levels of antinutritional factors in legumes. Yet a substantial portion of this variation remains “dormant” within landraces, wild relatives, and gene bank accessions. Genetic resources from Vavilov’s centers of diversity contain not only alleles for high protein levels but also unique protein fraction compositions, mineral–protein interactions, and alleles that confer relative stability of quality traits even under stress conditions. Therefore, future breeding programs must strengthen pre-breeding and introgression pipelines, systematically connecting **local genetic resources → elite breeding lines → final cultivars**.

From the classical breeding perspective, mass, pedigree, and family selection, heterosis and GCA–SCA analyses, multi-environment trials, and stability analysis remain the foundational pillars of protein improvement in legumes. However, the widespread negative correlation between seed yield and protein concentration, coupled with strong G×E interactions, clearly demonstrates the limitations of single-trait selection. As such, breeding strategies must increasingly adopt multi-trait selection indices and target-environment-oriented schemes that jointly consider yield, protein percentage, protein yield, amino acid profile, digestibility, functional properties, and stress tolerance.

Modern molecular and genomic tools qualitatively transform this classical framework. Marker-assisted selection (MAS) enables precise tracking of major QTLs related to specific protein

fractions, phytate content, and antinutritional factors. Genomic selection (GS) accelerates genetic gain for polygenic traits such as protein content, protein yield, and amino acid balance. QTL/GWAS and pangenomic approaches enable the identification of stable, environment-independent candidate regions, advancing legume breeding toward a data-driven, **prediction-based paradigm**. Additionally, CRISPR/Cas genome editing opens the door to a new era of "precision breeding," targeting modifications to storage proteins, reductions in antinutritional components, and improvements in mineral bioavailability.

High-throughput phenotyping (HTP) and phenomic platforms serve as complementary components that strengthen the link between genomic information and field performance. Drone- and satellite-based multispectral/hyperspectral imaging, automated systems for monitoring root/nodule traits and growth dynamics, and NIR and hyperspectral seed-scanning technologies enable high-resolution monitoring of physiological processes related to protein accumulation, nitrogen-use efficiency, and nodule activity. These advances enhance the accuracy of GS and QTL models and shorten breeding cycles. In the near future, artificial intelligence and machine-learning-driven analytics are expected to play a key role in integrating genomic, phenomic, and environmental datasets.

In conclusion, developing next-generation legume cultivars capable of meeting global plant protein demand requires a multidimensional framework that integrates genetic resource management, classical breeding, genomic and omic technologies, advanced phenotyping infrastructures, and food science. The creation of legume varieties with tailored quality profiles for functional foods, plant-based meat, dairy alternatives, and other emerging products will form a central focus of future breeding efforts. In this context, strong collaborations among public research institutions, universities, the private sector, and the food industry will be essential to strengthen the role of legumes in closing the global protein gap and facilitating the transition toward sustainable food systems.

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LEGUMES IN THE AGE OF GLOBAL WARMING: PHYSIOLOGICAL STRESS RESPONSES AND PRODUCTION RISKS

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ABSTRACT

With the acceleration of global warming, the increasing frequency of heat waves, prolonged drought periods, and irregular precipitation regimes has become a significant determinant of physiological functioning and production reliability in legumes. The simultaneous occurrence of drought and heat stress triggers multilayered physiological disruptions, including reduced photosynthetic capacity, altered stomatal behavior, impaired carbon–nitrogen metabolism, excessive reactive oxygen species accumulation, and compromised antioxidant defense systems. The reproductive phase is susceptible to high temperature; reductions in pollen viability, impaired anther dehiscence, decreased stigma receptivity, and sharp declines in pod-setting rates collectively intensify yield losses. In addition, nodulation and biological nitrogen fixation are highly vulnerable to climatic stresses, and the weakening of the *Rhizobium*–plant symbiosis adversely affects both plant nitrogen nutrition and soil fertility. Current literature indicates that yield reductions of 30–60% are common in legumes under combined drought and heat stress. This review synthesizes contemporary findings on legume physiological stress responses to global climate change and elucidates the core mechanisms underlying production risks. Overall, the evidence highlights the need to develop multi-stress tolerance and to adopt integrated physiological, ecophysiological, and genetic strategies to ensure sustainable legume production.

Keywords: Legumes, Global Warming, Drought Stress, Physiological Response, Production Risk

1. Introduction

With the acceleration of global warming, the increasing frequency of heat waves, irregular precipitation regimes, prolonged drought periods, and extreme climatic events has emerged as a significant environmental pressure threatening the production stability of cool-season legumes such as chickpea, lentil, and faba bean. The impacts of climate change on agricultural production are now recognized not merely as yield-reducing factors but as a complex, multilayered stress matrix that influences virtually all plant physiological processes. Andrews and Hodge (2010) emphasize that global warming weakens production security by pushing temperature thresholds beyond the tolerance limits of cool-season legume-growing regions. In contrast, Kaushal et al. (2016) highlight that rising temperatures can induce critical disruptions in plant metabolism. Collectively, these observations indicate that climate-related stress has evolved from an episodic constraint into a structural threat transforming legume production systems.

The simultaneous occurrence of drought and heat stress synergistically impacts legume physiology, substantially intensifying damage severity. Farooq et al. (2009) reported that drought disturbs cellular water balance, restricts photosynthesis, increases osmoprotectant synthesis, and reshapes hormonal regulation, while heat stress accompanies these responses with additional mechanisms, including impaired protein stability, excessive accumulation of reactive oxygen species (ROS), and loss of membrane integrity. The combination of drought and heat suppresses carbon–nitrogen metabolism, weakens defense systems, and induces rapid physiological deterioration, particularly in reproductive tissues. Thus, contemporary literature underscores that combined stresses, not individual stresses, are the most decisive drivers of climate-induced yield losses.

The most pronounced vulnerability in legume production emerges during the reproductive phase. High temperatures severely reduce pollen viability, stigma receptivity, and pollen tube growth, thereby markedly lowering pod-set rates. Sita et al. (2017) reported that heat stress denatures pollen proteins and limits fertilization success, while Gaur et al. (2015) identified pollen development as the most temperature-sensitive reproductive process, noting that once critical thresholds are surpassed, a substantial proportion of flowers become abortive. These findings clearly demonstrate that generative success is the weakest link in legume climate resilience.

The production-level consequences of drought and heat stress have been widely documented globally. In a meta-analysis of 65 independent studies, Daryanto et al. (2015) found that drought reduces legume yields by an average of 30–40%, with losses reaching up to 60% during flowering. When heat stress accompanies drought, yield declines escalate dramatically. Kumari et al. (2021) likewise reported that drought–heat combinations critically impair pollen viability, floral integrity, and pod-set in cool-season legumes. These findings indicate that the impacts of global warming on legume production have shifted from periodic constraints to systemic production risks.

Taken together, the evidence clearly demonstrates the strong linkage between legume physiological stress responses and the production risks posed by climate change. The weakening of key mechanisms such as photosynthesis, water-use efficiency, antioxidant defense, reproductive biology, and biological nitrogen fixation threatens the strategic ecological and nutritional role of legumes. Therefore, sustainable legume production requires an integrative framework that combines agronomic practices, physiological adaptation, and genetic improvement strategies. This review aims to evaluate the physiological stress responses

of legumes under global warming, elucidate the primary mechanisms underlying production risks, and discuss future adaptation strategies from a multidimensional perspective.

2. Cellular Damage Mechanisms Under Heat Stress: ROS Accumulation, Antioxidant Response, and Photostructural Disruption

The physiological pressure imposed by heat stress in legumes is closely associated with rapid metabolic disturbances that arise at the cellular level. Elevated temperatures reduce the stability of photosynthetic pigments, accelerate chlorophyll degradation, and increase the susceptibility of photosystem II (PSII) to photodamage. Andrews and Hodge (2010) reported that cool-season legumes are unable to maintain photochemical efficiency at temperatures exceeding 30–35 °C, and their protective capacity against light-induced damage declines sharply under such conditions. Heat also enhances membrane fluidity, disrupting ion homeostasis—a critical factor that limits both energy synthesis and carbon fixation.

One of the most prominent consequences of heat stress is the rapid accumulation of reactive oxygen species (ROS). Kaushal et al. (2016) demonstrated that elevated temperature dramatically increases ROS production in both mitochondria and chloroplasts, leading to lipid peroxidation and protein oxidation. Although antioxidant defense systems (SOD, CAT, APX, GR) initially attempt to buffer ROS accumulation, prolonged stress eventually overwhelms their capacity, leading to irreversible oxidative damage and widespread cellular dysfunction.

Sita et al. (2017) emphasized that heat stress induces ROS accumulation, particularly rapidly in reproductive tissues, producing profound effects on pollen viability. Due to the intrinsic heat sensitivity of pollen proteins, increased oxidative stress slows pollen tube elongation and reduces fertilization success. This mechanistic disruption limits not only reproductive performance but also weakens embryo development and pod filling, making the impact of heat stress on yield inherently multilayered.

Heat stress further reduces carbon assimilation by inhibiting Rubisco, the key enzyme governing the dark reactions of photosynthesis. Farooq et al. (2009) noted that elevated temperature destabilizes the three-dimensional structure of proteins, compromising carbon metabolism and placing plants in an energy-deficient state. Energy shortages diminish both defense capacity and new tissue formation, significantly increasing plant vulnerability. Gaur et al. (2015) similarly reported that heat disrupts the electron transport chain, limiting ATP production and directly impairing physiological processes occurring during flowering.

Collectively, these findings illustrate that heat stress in legumes is far more than a superficial temperature challenge; rather, it is a complex stressor that triggers cascading metabolic and cellular reactions. Processes such as ROS accumulation, collapse of antioxidant defenses, photostructural degradation, and suppression of carbon metabolism represent core physiological drivers of heat-induced yield losses. Therefore, the development of heat-tolerant genotypes must target not only macro-level agronomic performance but also the underlying cellular mechanisms that confer resilience.

3. Vulnerability of Nodulation and Biological Nitrogen Fixation Under Climate Stress

One of the significant advantages of legumes in agricultural systems is their ability to enrich soils with natural nitrogen through biological nitrogen fixation (BNF). However, this process is susceptible to climatic stresses. Elevated temperature and drought slow the Rhizobium infection process, restrict nodule formation, and weaken overall symbiotic efficiency. Andrews and Hodge (2010) reported that increasing temperatures suppresses nodule development in cool-season legumes, leading to reductions in both nodule number and effectiveness. This decline negatively affects not only plant nitrogen nutrition but also seed protein concentration.

Kumari et al. (2021) demonstrated that the combined effects of drought and heat significantly reduce BNF capacity and sharply decrease nodule biomass under stress. Declining water potential within nodules disrupts oxygen diffusion and leghaemoglobin activity, directly limiting bacterial respiration and N_2 fixation. Farooq et al. (2009) further noted that drought reduces carbon supply, thereby reducing the energy flow to nodules and imposing strong constraints on bacterial metabolism. Oxidative damage in nodule tissues induces premature senescence under prolonged stress.

In their global meta-analysis, Daryanto et al. (2015) showed that legume yields decline by an average of 30–40% under drought, and reductions in BNF capacity are among the primary drivers of these losses. Insufficient nodulation forces the plant to rely entirely on external nitrogen inputs (fertilizers), diminishing both economic and environmental sustainability. Kaushal et al. (2016) also reported that rising temperatures slow the development of infection threads and suppress the activity of *Rhizobium* strains.

The effects of heat stress during the reproductive period are directly interconnected with symbiotic nitrogen fixation. Sita et al. (2017) emphasized that reproductive tissues have a high carbon demand, and reductions in photosynthetic capacity under stress further limit carbon allocation to nodules. This exacerbates declines in BNF and reduces flowering success due to nitrogen deficiency. Gaur et al. (2015) also noted that when temperature thresholds are exceeded, enzymatic activities in nodules are impaired, potentially leading to near-complete cessation of nitrogen fixation.

Collectively, these findings highlight that BNF is among the most fragile physiological processes in legumes under climate change. Nodule development, Rhizobium activity, carbon–energy flow, and oxygen regulation are concurrently targeted by both drought and heat. Therefore, breeding for climate-resilient legume genotypes must focus not only on plant physiological traits but also on enhancing stress tolerance in symbiotic interactions.

4. Genomic, Metabolic, and Molecular Approaches to Enhancing Climate Resilience

The increasing severity of climate stresses highlights the need for innovative molecular and genomic approaches that extend beyond traditional breeding methods in legumes. Modern breeding programs have shifted toward elucidating the physiological and molecular mechanisms underlying stress tolerance. Kaushal et al. (2016) reported that numerous genes contribute collectively to heat and drought tolerance, with antioxidant defense genes, heat shock proteins (HSPs), and osmoprotectant biosynthesis pathways playing central roles. Consequently, genetic selection must adopt an integrative strategy that targets multiple stress-response networks simultaneously.

Farooq et al. (2009) emphasized the importance of osmotic regulators (proline, glycine betaine), membrane-stabilizing compounds, and ROS-detoxifying enzymes in drought response, suggesting that these mechanisms represent promising targets for molecular breeding efforts. Modern breeding tools, particularly genomic selection (GS) and marker-assisted selection (MAS), enable early identification of stress-tolerance genes, thereby accelerating breeding cycles and facilitating the rapid development of climate-resilient cultivars.

Sita et al. (2017) highlighted the sensitivity of reproductive biology to heat stress, emphasizing that genes protecting pollen development represent strategic targets for breeding programs. Gaur et al. (2015) further noted the importance of genes that maintain photochemical efficiency and sustain energy balance during flowering in the development of heat-tolerant legume genotypes. Understanding the genetic regulation of these mechanistic pathways is fundamental to designing effective, climate-resilient breeding strategies.

Findings from Kumari et al. (2021) and Daryanto et al. (2015) underscore the economic and ecological significance of developing genotypes with combined drought and heat tolerance. Such genotypes not only mitigate yield losses but also support the long-term sustainability of biological nitrogen fixation. Enhancing *Rhizobium* strains' tolerance to temperature and drought is likewise critical for improving the resilience of the symbiotic system.

Among the most promising future-oriented approaches is CRISPR-Cas-based targeted gene editing. This technology enables precise modification of genes encoding heat shock proteins, ROS-detoxification enzymes, stomatal-regulation components, and nodule-development factors. Through these interventions, it becomes possible to engineer comprehensive stress responses at both the plant and symbiont levels. In conclusion, legume breeding in the era of global warming is undergoing a multidisciplinary transformation that requires integrating physiological, molecular, and ecophysiological knowledge into holistic improvement strategies.

5. Conclusion

In the era of accelerating global warming, legumes are increasingly vulnerable to both drought and heat stress. The reviewed literature clearly demonstrates that the combined effects of drought and heat are far more destructive than the effects of either stress alone, targeting virtually all aspects of plant physiology. Suppression of photosynthesis reduced stomatal conductance, ROS-induced cellular damage, hormonal imbalance, and weakened carbon–nitrogen metabolism, collectively restricting both vegetative growth and reproductive performance. This poses a substantial production risk for legumes, which are among the primary global sources of plant-based protein.

Reproductive development has consistently been identified as the most climate-sensitive stage, as shown by both recent studies (Kumari et al., 2021; Sita et al., 2017) and foundational literature (Gaur et al., 2015; Kaushal et al., 2016). Declines in pollen viability, impaired anther dehiscence, reduced stigma receptivity, and weakened embryo development lead to severe reductions in pod-set rates. These findings indicate that climate-induced yield losses in legumes fundamentally arise from disruptions in reproductive physiology. Therefore, future breeding efforts must prioritize genetic mechanisms that safeguard reproductive biology under thermal and water stress.

At the same time, biological nitrogen fixation (BNF), a key ecosystem service provided by legumes, is strongly compromised under climate stress. Heat and water deficits limit Rhizobium infection, nodule formation, and nitrogenase activity, thereby reducing both plant nitrogen acquisition and soil fertility. Findings by Andrews and Hodge (2010) and Daryanto et al. (2015) show that climate change affects not only plant productivity but also the soil–plant–microbe continuum. Consequently, symbiotic resilience must be integrated into legume breeding strategies to enhance climate tolerance.

From a breeding perspective, current literature underscores the need for a holistic approach targeting multi-stress resilience. Studies such as Kaushal et al. (2016) and Farooq et al. (2009) highlight the critical roles of osmoregulation, antioxidant defense, membrane stability, and energy management in stress tolerance. In contrast, Gaur et al. (2015) and Sita et al. (2017) emphasize the strategic importance of protecting reproductive tissues under high temperature. When combined with modern breeding technologies, genomic selection, marker-assisted selection, and CRISPR-based gene editing, these mechanistic insights provide a robust foundation for developing climate-resilient legume cultivars.

In conclusion, sustainable legume production under global warming requires a multidimensional framework that integrates physiological, ecophysiological, microbiological, and genetic mechanisms. Scientific evidence indicates that future legume breeding must aim not only to enhance stress tolerance but also to strengthen symbiotic efficiency, resource-use effectiveness, and overall adaptive capacity. Therefore, breeding strategies that prioritize interdisciplinary integration, focus on stress combinations, and are supported by modern genomic tools will be essential to ensuring legume production stability under climate change.

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EVALUATION OF LEGUMES IN TERMS OF NUTRITIONAL AND TECHNOLOGICAL QUALITY IN THE CONTEXT OF SUSTAINABLE ALTERNATIVE PROTEIN SOURCES

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ABSTRACT

The growing global demand for sustainable protein sources has elevated legumes to a strategic position both nutritionally and technologically. Legumes serve as a crucial raw material for the alternative protein industry due to their high protein content, balanced amino acid profiles, and rich fiber and bioactive compound structures. However, the functional properties of protein fractions (solubility, gel formation, water and fat retention capacity, emulsification) are decisive factors in the development of new-generation food products such as plant-based meat and milk analogues. Reducing anti-nutritional components, improving digestibility, and the effects of processing methods (fermentation, sprouting, extraction techniques) on protein quality are at the center of current research. This review comprehensively examines the potential of legumes as a sustainable alternative protein source, covering nutritional quality, technological functionality, environmental benefits, and industrial applications. The findings indicate that legumes play a critical role in both human nutrition and the growing plant-based protein sector. That comprehensive innovation in breeding, processing technologies, and functional food applications will be needed in the future.

Keywords: Legumes, Alternative Protein Sources, Protein Quality, Functional Properties, Sustainable Nutrition

1. Introduction

Global population growth, shifting dietary habits, and environmental constraints have made the demand for sustainable protein sources more critical than ever. The EAT–Lancet Commission (Willett et al., 2019) emphasizes that plant-based proteins should occupy a central role in future food systems, while the large-scale analysis of Poore and Nemecek (2018), covering 38,000 farms and 40 crop types, demonstrates that legumes are significantly more sustainable than animal proteins in terms of carbon footprint, water use, and land requirements. Therefore, legumes have become essential components of sustainable food strategies both environmentally and nutritionally.

Beyond their sustainability advantages, legumes serve as a strategic raw material for the alternative protein industry due to their high protein content (20–30%), balanced amino acid composition, and rich dietary fiber profiles (Day, 2013). However, protein quality depends not only on quantity but also on digestibility, heat reactions, and processing methods, and levels of anti-nutritional factors such as trypsin inhibitors (Nosworthy et al., 2017). Current studies indicate that cooking, fermentation, germination, and fractionation can increase amino acid bioavailability, thereby enhancing the nutritional value of legume proteins (Acquah et al., 2021).

In addition to nutritional quality, the technological and functional properties of legume proteins are crucial for the development of next-generation foods, such as plant-based meat and dairy analogs. Water- and fat-binding capacities, emulsifying ability, foaming, and gelation characteristics determine texture, stability, and sensory attributes (Boye et al., 2010). Protein fractions from pea, faba bean, and chickpea stand out as strong alternatives in meat analog applications due to their high gelation capacity and thermal stability (Lam et al., 2018). Emerging technologies, such as high-moisture extrusion, enable the formation of fibrous, meat-like structures, expanding the industrial use of legume proteins (Barnés-Calle et al., 2024).

Another factor enhancing the technological value of legumes is the production of protein concentrates and isolates through dry fractionation and wet extraction. These approaches not only improve functional properties but also offer environmental benefits by reducing energy consumption (Pelgrom et al., 2013). In particular, pea protein isolates have gained widespread commercial use due to their gluten-free nature, relatively neutral flavor profile, and high solubility/gelation performance. Furthermore, biotechnological approaches, such as fermentation and enzymatic modification, offer opportunities to reduce undesirable flavor compounds and enhance functionality (Emkani et al., 2022).

Taken together, legumes are not only sustainable and cost-effective protein sources but also versatile ingredients that meet the industrial demands of modern food production. Their environmental benefits, high nutritional value, compatibility with advanced processing technologies, and increasing consumer demand position legumes strategically in the alternative protein market. Nevertheless, further research and technological development are required to enhance protein functionality, reduce anti-nutritional compounds, improve sensory qualities, and optimize emerging processing techniques.

2. Legume Proteins

Legumes are among the most prominent plant protein sources due to their nutritional quality, functional versatility, and potential for sustainability. Highlighting that plant proteins are among the key resources that can contribute to global food security, Day (2013) notes that legumes offer a strategic alternative to traditional animal proteins, particularly because of their high protein density and broad ecological adaptability. The significant protein fractions in

legumes, globulins (notably legumin and vicilin) and albumins, are structural components that determine both nutritional quality and functional behavior. Their high bioavailability makes legumes a crucial plant-based protein source for human nutrition.

From a food industry perspective, the functional properties of legume proteins are among the most critical factors influencing their use. Boye et al. (2010) report that legume proteins exhibit key functionalities, including water-holding capacity, gelation, emulsification, and foam stability, and that these traits vary depending on the protein fraction and processing method. Furthermore, the molecular structures of proteins and their responses to environmental factors (pH, ionic strength, temperature) enable the integration of legumes into a variety of products. Improving functional performance is closely related to extraction methods, denaturation levels, and the rearrangement of protein fractions.

Among legume proteins, pea protein has recently attracted considerable interest due to its nutritional and technological advantages. Lam et al. (2018) extensively examined the structural characteristics, extraction methods, and functional properties of pea protein isolates, demonstrating their high performance in gel formation, solubility, and emulsification capacity. The near-neutral flavor profile, low allergenicity, and high thermal stability of pea proteins make them among the most preferred protein sources in emerging plant-based food products, such as meat and dairy analogs. Furthermore, modern processing technologies such as high-moisture extrusion enable the formation of fibrous, meat-like textures in pea proteins.

The fundamental biochemical mechanisms governing the functional behavior of legume proteins are associated with the structural arrangements of their molecular components. Shevkani et al. (2019) emphasize that changes in secondary structures (α-helix and β-sheet) significantly influence critical technological properties such as gelation, foaming, and emulsification. These structural modifications explain how different processing conditions affect protein stability, aggregation, and refolding capacity. The conformational responses of proteins to environmental stresses support the versatile industrial application of legume-based proteins.

The rising prominence of legume proteins in food technology is not only tied to their functional capabilities but also to their compatibility with principles of sustainable production. Examining plant-based meat development, Boukid (2021) reports that legumes meet functional protein requirements while enabling the formulation of environmentally low-impact products. Their ability to fix atmospheric nitrogen, relatively low water demand, and substantially smaller carbon footprint compared with animal proteins position legumes at the center of sustainable food system strategies. Therefore, legume proteins are increasingly regarded as highly valuable biological components for both food security and the development of next-generation functional foods.

3. Nutritional Quality, Digestibility, and Amino Acid Profile

The nutritional value of legumes is primarily determined by their protein content and amino acid composition. In a comprehensive evaluation of cooked Canadian legumes, Nosworthy et al. (2017) reported that legumes generally have high lysine content, making them an essential complement to cereal-based protein sources, which are typically lysine-deficient. However, the limiting levels of sulfur-containing amino acids, such as methionine and cysteine, prevent legumes from being considered a complete protein source on their own. Thus, from an amino acid profile perspective, legumes provide higher nutritional quality when used in complementary protein strategies within plant-based diets.

Protein digestibility is another critical parameter determining nutritional quality. Nosworthy et al. (2017) demonstrated that DIAAS and PDCAAS values for different legume species vary with processing conditions, with cooking enhancing digestibility but potentially imposing limitations on specific amino acids in some species. The factors with the greatest influence on digestibility include cell wall integrity, starch–protein interactions, and levels of anti-nutritional components, such as trypsin inhibitors. Reducing or inactivating these compounds during processing markedly improves the bioavailability of legume proteins. Therefore, processing technologies are essential tools for enhancing the nutritional value of legumes.

Another essential aspect in the nutritional evaluation of legumes involves aroma compounds and sensory perception. Roland et al. (2017) noted that aroma in legume ingredients primarily originates from volatile compounds, lipid oxidation products, and degradation of specific amino acids. Characteristics described as “beany” or “grassy” can strongly influence consumer acceptance, especially for plant protein isolates. The interaction between amino acid profiles and lipid content, combined with Maillard reactions during processing, determines both nutritional and sensory quality.

Aroma components affect not only sensory attributes but also indirectly influence the potential application of proteins. According to Roland et al. (2017), certain aromatic compounds can be reduced through processing techniques, expanding the applicability of legume proteins, particularly in plant-based meat and dairy analogs. In this context, control of specific volatile compounds, optimization of processing conditions, and improved understanding of the chemical transformations of aroma-related amino acids all contribute to enhancing both the nutritional and industrial value of legume proteins. In summary, nutritional quality, digestibility, and amino acid composition are three complementary and fundamental parameters that position legume proteins as sustainable and functional components in modern food systems.

4. Technological Functionality (Emulsification, Gelation, Fractionation, Extrusion)

The technological functionality of legume proteins is one of the most critical attributes determining structure, stability, and sensory quality in food products. This functionality is closely associated with the molecular structure of proteins, their responses to environmental conditions, and the processing techniques applied. In particular, pea and faba bean proteins are widely used in modern plant-based food formulations because of their strong performance in emulsification, gelation, and foaming. Pelgrom et al. (2013) showed that dry fractionation yields high-efficiency pea protein concentrates that preserve functional properties, with significant improvements in water-holding capacity and dispersibility. This finding positions dry fractionation, which is more energy-efficient, as an effective method for producing sustainable ingredients enriched in functional proteins.

The technological behavior of protein fractions varies markedly depending on the processing techniques used. Cui et al. (2020) demonstrated that different processing treatments (thermal treatments, pH adjustments, physical modifications) induce distinct effects on the structure of yellow pea protein isolates, directly influencing their emulsification and gelation capacities. Denaturation triggered by temperature and pH exposure can increase gel firmness by exposing hydrophobic regions and enhancing protein–protein interactions. Conversely, uncontrolled aggregation may reduce solubility, negatively affecting emulsion stability. Thus, optimizing physicochemical conditions during processing is essential for maximizing the functional performance of legume proteins.

Faba bean proteins also hold substantial industrial potential due to their functional properties. Krause et al. (2023) reported that compositional differences and extraction methods significantly affect the functional characteristics of faba bean protein isolates, including water-holding capacity, viscosity, and gel formation. The study further revealed that interactions between proteins and polyphenols, as well as proteins and starch, influence gel stability and may vary across cultivars. These findings highlight that faba bean proteins represent promising alternatives as emulsifying and structuring agents in plant-based meat products and sauce/cream analogs. Additionally, interactions with polyphenols may support both functional and antioxidant properties, offering dual value.

Among the most advanced applications of legume proteins is their use in high-moisture extrusion (HME) technology. Barnés-Calle et al. (2024) demonstrated that chicken-like fibrous structures can be successfully formed when pea protein isolates are processed under high-moisture extrusion conditions. During extrusion, heat, shear force, and moisture content play decisive roles in protein alignment, denaturation, and restructuring. Non-covalent interactions between protein chains (hydrophobic interactions and hydrogen bonds) contribute to the formation of fibrous, layered textures. A comprehensive review by Sui et al. (2024) explains the fundamental mechanisms underlying plant proteins' ability to form meat-like structures. It emphasizes that optimizing extrusion parameters is essential for industrial product quality.

The technological functionality of legume proteins is substantially shaped by processing techniques such as fractionation, structural modification, and extrusion. Core functionalities such as emulsification and gelation play key roles in meeting the formulation needs of modern plant-based products. The ability of dry fractionation to provide sustainable and energy-efficient protein ingredients enhances the value of pea and faba bean proteins. At the same time, high-moisture extrusion enables the development of realistic textures in plant-based meat analogs. Thus, data-driven optimization and molecular-level understanding of protein structure strengthen the central position of legume proteins in the functional food systems of the future.

5. Environmental Sustainability and Global Nutrition Context

Global food systems lie at the center of multidimensional environmental challenges, including greenhouse gas emissions, land use, water consumption, and biodiversity loss. In a comprehensive analysis involving more than 40,000 farms across 119 countries, Poore and Nemecek (2018) demonstrated that the environmental footprint of animal-based foods is substantially higher than that of plant-based foods. Their findings emphasize that legumes rank among the lowest-impact protein sources in terms of carbon footprint and water consumption, and that shifting toward plant-based proteins will be decisive for increasing the sustainability of food systems. Reducing land use, lowering greenhouse gas emissions, and minimizing production-related pollution are critical goals that, together, reinforce legumes' strategic position in the food chain.

Studies on sustainable dietary models indicate that plant proteins, especially legumes, provide an optimal balance for both human and planetary health. In the EAT–Lancet Commission report, Willett et al. (2019) introduced the concept of the “Planetary Health Diet,” highlighting the key role of plant-derived proteins in transforming food systems. According to the report, legumes should be central components of sustainable dietary patterns due to their high nutrient density, low environmental impact, and reduced demand for natural resources during production. Furthermore, legumes were identified as a critical protein source for low-income populations, supporting both economic accessibility and long-term public health objectives.

Food security has become increasingly fragile in recent years due to climate variability, political instability, and pandemic-related disruptions. The FAO (2021) states that approximately 720–811 million people are undernourished globally, and that these numbers continue to rise. The report underscores that resilient, low-cost plant protein sources, such as legumes, play a crucial role in addressing nutritional deficiencies, particularly in low- and middle-income countries. Beyond protein, legumes offer significant amounts of dietary fiber, vitamins, and minerals, making them valuable tools in reducing both undernutrition and obesity-related burdens.

In summary, within the context of environmental sustainability and global nutrition systems, legumes are a key focus of modern food policy due to their low environmental footprint, high nutritional value, and broad accessibility. Considered together, the ecological analyses of Poore and Nemecek (2018), the sustainable diet recommendations of Willett et al. (2019), and the global food security assessments of FAO (2021) clearly demonstrate that legumes are indispensable both ecologically and socioeconomically. In the future, increasing the effective utilization of legumes throughout production, processing, and consumption will be critical for safeguarding planetary health and improving human nutrition.

6. Functional Properties, Nutritional Value, and Alternative Protein Approaches in Legumes

International literature extensively demonstrates that legume proteins are strong alternative protein sources in both nutritional and technological contexts. Boye et al. (2010) reported that legume proteins possess critical functional properties, including gelation, emulsification, and water-holding capacity, and that these properties vary depending on the fraction type and processing method. The significant protein fractions, globulins and albumins, play a central role in determining protein structure and functionality, supporting the versatile use of legumes within the food industry. These findings reinforce the notion that legumes are not only nutrient-dense foods but also valuable functional ingredients.

From a nutritional standpoint, legumes play a significant role in plant-based diets due to their high lysine content and rich fiber content. Nosworthy et al. (2017) demonstrated that, according to global criteria such as DIAAS and PDCAAS, legumes constitute high-quality protein sources and that cooking and other processing methods positively influence protein digestibility. Studies focusing on antioxidant capacity and bioactive compounds further support this view. For example, Rochfort and Panozzo (2007) reported that legumes contain beneficial components such as polyphenols, flavonoids, and saponins, while Champ (2002) highlighted that anti-nutritional factors can be substantially reduced through appropriate processing techniques. Collectively, these results indicate that legumes provide comprehensive benefits to human health.

The body of research on technological functionality has focused particularly on pea and faba bean proteins. Lam et al. (2018) demonstrated that pea protein isolates exhibit high functionality in solubility, gelation, and emulsification, and that these properties can be optimized through targeted extraction methods. Shevkani et al. (2019) reported that secondary structural components (α-helices and β-sheets) are closely linked to functional performance, emphasizing the importance of protein engineering and processing optimization. Overall, these studies highlight the high potential of legume proteins for providing texture, stability, and structural integrity in modern food formulations.

In the alternative protein industry, legumes are increasingly recognized as critical building blocks. Boukid (2021) described how pea and faba bean proteins have become foundational materials for plant-based meat analogs, while Osen et al. (2014) demonstrated that pea proteins

can form fibrous, meat-like structures through high-moisture extrusion. Sha and Xiong (2020) further analyzed the technological challenges of plant-based meat products, including protein–protein interactions and texture optimization. They showed that legume proteins are among the key biopolymers driving future innovations in this field.

In the context of environmental sustainability, the importance of legumes as protein sources becomes even more pronounced. In their large-scale meta-analysis, Poore and Nemecek (2018) found that legumes have significantly lower environmental impacts than animal proteins, including carbon footprint, land use, and water consumption. These findings illustrate that legume proteins are not only nutritionally or technologically valuable but also strategically crucial for environmental sustainability. Therefore, international literature strongly supports the conclusion that legumes represent fundamental protein sources for both food science and sustainable agricultural policy frameworks.

7. Conclusion

Legumes have gained a central position in today's sustainable food systems due to their high nutritional value, functional protein properties, and low environmental impact. Rising global nutritional demands combined with ecological pressures have accelerated the need for plant-based proteins, positioning legumes as strong alternatives to traditional animal-derived products. The literature clearly demonstrates that legumes, with protein contents ranging between 20–30%, rich amino acid profiles, high dietary fiber levels, and diverse bioactive compounds, hold strategic importance for both human health and functional food production.

The structure–function relationships of protein fractions make legume proteins highly valuable within food processing technologies. Protein isolates derived from species such as pea and faba bean have become key components in plant-based meat and dairy analogs due to their critical technological attributes—gelation, emulsification, water-holding capacity, and solubility. Modern processing approaches—including dry fractionation, wet extraction, fermentation, and high-moisture extrusion—enhance functional performance and expand industrial application. These findings highlight that legume proteins are not merely nutritional resources, but also high-value biopolymers capable of providing structure and stability in innovative food designs.

From a nutritional perspective, legumes play a critical role in plant-based diets owing to their high lysine content and potential health benefits. Although certain anti-nutritional factors and limiting amino acids exist, these can be minimized through appropriate processing techniques, considerably improving protein digestibility. The management of aroma compounds is an important research area for improving consumer acceptance. Collectively, these insights demonstrate that multidisciplinary approaches are required to enhance the sensory and nutritional appeal of legumes.

In terms of environmental sustainability, legumes have a markedly lower carbon footprint, water consumption, and land-use requirements than animal protein sources—these characteristics position legumes as strategic components in both climate change mitigation efforts and global food security solutions. Reports on food security and global health models indicate that legumes offer affordable, nutritionally valuable options, particularly in low-income and climate-stressed regions.

Legumes sit at the intersection of sustainable agriculture, healthy nutrition, functional food development, and alternative protein technologies. Future research should focus on optimizing functional properties of protein fractions, advancing innovative processing techniques such as extrusion and fermentation, improving aroma and sensory qualities, and leveraging environmental advantages more effectively. Taken together, current evidence clearly shows that legumes will remain indispensable components of both present and future food systems.

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ECONOMICS OF PLANT BREEDING: OPTIMIZATION AND COST–BENEFIT FRAMEWORK

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ABSTRACT

This study approaches plant breeding not merely as the manipulation of genetic variation, but as a strategic activity integrated with economic decision-making processes. The modern breeding paradigm goes beyond classical selection models by incorporating demand-led, market-oriented, and economically optimized approaches. Product profiles, adoption analysis, cost–benefit assessment (CBA), economic weights, and selection indices enable investment-based management of breeding programs. The shortening of breeding cycles through genomic selection, together with reductions in cost and improvements in economic efficiency, represents a critical advantage of modern breeding. It is undeniable that plant breeding constitutes a multidimensional development tool extending from micro-scale biological processes to macro-scale economic impacts (productivity, welfare, food security, employment). In conclusion, plant breeding has become a fundamental component of sustainable agricultural development through the integration of strategic planning, economic modeling, and genetic innovation.

Keywords: Plant breeding; economic optimization; demand-led breeding; selection indices; adoption.

1. Introduction

Plant breeding is a systematic scientific discipline that aims to improve populations for targeted traits through the controlled manipulation of genetic variation. Falconer & Mackay (1996) describe this process as a quantitative genetics–based progression, whereas Acquaah (2020) notes that modern breeding encompasses a broad range of techniques, including both classical and genomic approaches. Bernardo (2020) emphasizes that the breeder is not only a scientific practitioner but also a strategic decision-maker and resource manager, highlighting the multidisciplinary nature of breeding. Thus, breeding extends beyond population genetics, ecology, and molecular biology to include decision-making mechanisms such as data management, program planning, and risk analysis. Acquaah (2020) states that within quantitative genetics, breeding is not a random process but a strategically directed path of genetic improvement. Therefore, breeding is not only a scientific system but also a managerial and design-oriented activity.

Beyond traditional definitions, modern efforts increasingly incorporate market-led and demand-led breeding approaches. Persley & Anthony (2017) demonstrate that breeding is not merely a biological process occurring in laboratories and fields, but a business model that must be designed for markets and users. Ragot et al. (2018) show that this includes fundamental processes such as developing product profiles and translating demand signals into strategic decision mechanisms. Stakeholder analysis, identification of target environments, and translation of market needs into genetic objectives form the essence of the demand-led approach (Yao et al., 2017). This framework allows breeding design to be viewed not only in terms of biological performance but also in terms of its capacity to create economic value. The demand-led model positions breeding as a mechanism for sustainable development.

Plant breeding is also strategically crucial from an economic perspective. Groenewegen et al. (2016) report shows that breeding generates benefits far exceeding costs by increasing farmer income, agricultural productivity, and national economic performance. The CAS–CGIAR (2020) report similarly indicates that modern breeding strategies generate net economic contributions worth millions of dollars. Therefore, economic optimization is a fundamental criterion for evaluating the performance of breeding programs. Economic weights (Batista et al. 2021) quantify the value of selected traits for farmers and markets, facilitating strategic decision-making. Breeding without economic evaluation yields only biological progress, while the economic impact remains unaccounted for. The modern literature clearly supports the use of economic modeling to manage breeding.

This economic orientation becomes even stronger when combined with genomic techniques and selection indices. Numerous studies have confirmed that genomic selection shortens the breeding cycle and increases economic efficiency (Heffner et al., 2009; Merrick et al., 2022). Selection indices enable decision-making based on scientific and economic rationality among multiple traits, reinforcing strategic direction (Batista et al. 2021). Cost–benefit analysis (CBA) facilitates the identification of the most appropriate breeding pathway by comparing the cost-effectiveness of alternative strategies (Groenewegen et al., 2016; CAS–CGIAR, 2020). The integration of these tools has transformed modern breeding programs into “genetically based investment systems”.

It is essential to measure economic impact at the societal level. Adoption represents the ultimate indicator of the commercial and financial success of breeding, because varieties not used by farmers do not generate economic value (CAS–CGIAR, 2020). Noleppa & Cartsburg (2021) demonstrated that breeding has macroeconomic rather than microeconomic impacts, enhancing national income, employment, and societal welfare. Therefore, breeding programs should

produce not only genetic gains but also economic and social transformation. Modern breeding is a multidisciplinary field that requires economic modeling, strategic planning, and development-impact assessment beyond biological improvement alone. Data clearly indicate that future breeding programs will simultaneously manage genetics and economics, establishing breeding as a core component of sustainable agricultural development.

2. Importance of Plant Breeding

Plant breeding is a systematic, scientific discipline that aims to improve target traits by directing and selecting genetic variation. Falconer and Mackay (1996) define plant breeding as a quantitative genetics–based progression process in which allele frequencies are intentionally altered to enhance populations. Acquaah (2020) states that breeding encompasses a broad spectrum of methodologies ranging from classical hybridization and selection to genomic selection, from phenotypic evaluation to marker-assisted approaches. According to Bernardo (2020), breeding is not merely about manipulating genes but involves a systematic process of managing decisions, risks, and outcomes; therefore, the breeder is not only a scientific specialist but also a strategic decision manager. Breeding is simultaneously the integration of genetic knowledge, environmental interactions, and economic realities; thus, "data-driven decision-making" and "program organization" are fundamental prerequisites. From a quantitative genetic perspective, Acquaah (2020) emphasizes that breeding is not a random endeavor but a strategically directed genetic advancement. In this framework, breeding is a planned, predictable process that transforms plant populations using scientific principles.

The importance of plant breeding is both biological and economic. Bernardo (2020) indicates that breeding is a strategic solution to increasing pressures of population growth, food security, and agricultural productivity; therefore, the breeder is not only a geneticist but a "resource manager and strategic decision-maker." Acquaah (2020) highlights modern breeding as an essential tool for sustainable agriculture, stress tolerance, product quality, and adaptation. Particularly as global climate change, disease pressure, and production costs increase, breeding programs become critical for ensuring food supply and maintaining agricultural economies. Falconer and Mackay (1996) note that breeding not only drives genetic gain but transforms biological variation into economic output. Acquaah (2020) further defines the breeder's role as "manager–decision-maker," demonstrating that program success depends on strategic planning, objective setting, and resource allocation. In conclusion, plant breeding is an indispensable core technology for food security, productivity, quality, sustainability, and economic development.

3. Market-Led and Demand-Led Plant Breeding

Contemporary approaches no longer view plant breeding merely as a biological process aimed at genetic progress; rather, it is defined as a "business model" that requires strategic planning and managerial execution. Persley and Anthony (2017) characterize this approach as "market-led" breeding and emphasize that breeding design must be shaped by the needs of markets, users, and supply chains. The first step in demand-led breeding is accurately identifying the market's real needs. Transforming these needs into breeding objectives relies on product profiles and strategic planning pathways. As highlighted by Ragot et al. (2018), varietal development programs cannot achieve widespread adoption and commercial impact unless they generate "demand-designed solutions." Hence, breeding transcends classical scientific processes and incorporates concepts such as "strategic investment management" and "market alignment." Through demand-led breeding, breeding programs become more predictable, measurable, and sustainable. This framework maximizes both agricultural performance and the economic value generation capacity of the developed product.

Demand-led breeding is based on defining market segments, understanding user preferences, weighting value-defining traits using econometric analyses, and ultimately transforming product profiles into strategic decision-making tools. Yao et al. (2017) describe market-led breeding not as a purely technical process, but as a business model structured around economic rationality and stakeholder engagement. In the Demand-Led Breeding platform's documents, emphasis is also placed on "monitoring–evaluation (M&E)" and "performance indicators (KPI)." These explanations underline the importance of viewing breeding not as a research activity but as a "manageable production and investment process." Product profiles lie at the core of this approach, since they integrate biological and economic criteria. The demand-led framework also acknowledges that breeding serves not merely the end user but the "value chain." Therefore, market-led breeding drives decisions not only toward "genetic gain" but also toward "economic impact."

One of the most potent tools of demand-led breeding is the product profile. Ragot et al. (2018) emphasize that a product profile is not merely a list of target traits; it represents the formal, technical, and economic framework of the investment rationale (business case). The product profile defines "which traits" demand exists for and "with what economic weights." Persley and Anthony (2017) describe it not only as a biological selection tool but as the foundational input of the entire economic architecture of the breeding program. Stakeholder mapping identifies all actors in the market chain and tests the feasibility of the product profile; this analysis includes farmers, processors, traders, consumers, and public authorities. The Demand-Led Breeding approach requires the systematic application of these analyses. The "business case" logic implies that decisions regarding varietal development must be economically justified, reinforcing the investment character of breeding. Consequently, breeding transitions from being merely a "scientific project" to a "controlled investment process."

Viewing plant breeding as a business activity makes public–private sector partnerships a strategic domain. An economic analysis by Areal et al. (2014) demonstrated that financial diversification is essential for the sustainability of breeding. While public research institutions provide scientific infrastructure and risk management support, the private sector ensures commercial scaling and market dissemination. This division of roles creates strategic advantages, particularly for the rapid implementation of demand-led breeding. Sustainable economic models arise in areas such as organic breeding, niche market products, and quality-driven breeding (Nuijten et al., 2016). Thus, breeding programs create not only an "output product" but also "market impact." This model transforms varieties from products that farmers merely want into products the market is willing to pay for. Therefore, achieving sustainability in breeding is now achieved through the integration of financial planning, investment management, and value-chain analysis.

Demand-led breeding aims at much more than technical efficiency; its most critical output is socio-economic impact. Yao et al. (2017) emphasize that this approach gives rise to new training models and program management standards. As defined by Persley and Anthony (2017), the breeder is no longer merely a genetic expert, but also a "designer of investment pathways." Through the product profile approach, breeding success is measured not only by yield improvement but also by "adoption" and "market acceptance." Ragot et al. (2018) describe the strategic flow as "not from laboratory to market, but from market to breeding." When linked with public–private partnerships, strategic planning, and performance indicators, this model becomes a tool for sustainable development. Consequently, demand-led breeding transforms plant breeding from a purely genetic science into a strategically managed economic development sector of the future.

4. Economics of Plant Breeding and Strategic Planning

Plant breeding is not merely a biological activity aimed at achieving genetic gain; it is also a strategic economic process. The limited availability of resources in the agricultural sector necessitates the management of breeding programs through economic optimization. The requirement for economic optimization is shaped by the societal and industrial benefits that breeding programs deliver. A comprehensive cost–benefit assessment found that plant breeding programs yield multifaceted benefits for producers and agricultural economies (Groenewegen et al., 2016). The same study demonstrated that breeding generates tangible value not only genetically but also economically. In this context, economic optimization is essential for both scientific and financial sustainability. The CAS–CGIAR report similarly indicated millions of dollars in net economic contributions (CAS–CGIAR, 2020). Therefore, economic optimization is a fundamental performance criterion in plant breeding. Economically inefficient breeding strategies may lead to wasteful use of national resources. Accordingly, modern breeding programs must be evaluated using indicators such as return on investment, adoption rate, and market alignment. The primary purpose of economic optimization is to balance genetic progress with economic value creation. Thus, breeding programs serve not only biological success but also agricultural development and economic welfare.

Economic weights are parameters that determine how much improvement in a given trait contributes to producers' economic gains. This concept serves as the basis for selection indices. Selection conducted without economic weights produces only biological outcomes. Economic weights strengthen strategic decision-making mechanisms (Batista et al. 2021). Economic indices enable breeders to make scientifically rational decisions among multiple traits. This approach increases return on investment. Economic weights may vary from country to country or even region to region, because market dynamics differ geographically. Therefore, economic indices are not static but dynamic tools that must be continually updated. Selection decisions supported by economic analysis enhance resource efficiency within breeding programs. The concept of economic selection is a strategic principle guiding modern breeding. Moreover, economic weights establish a balance between producer preferences and consumer expectations. Accurate estimation of economic weights increases product competitiveness in the market. Incorrectly defined weights may create risks regarding time, cost, and success rates. Therefore, economic weights must be determined using scientific data, market analysis, and socioeconomic models. Ultimately, economic weights are critical tools for balancing the biological and economic dimensions of modern breeding.

Genetic gain describes the biological improvement achieved through breeding. Economic gain, however, refers to the return of that improvement in terms of income, market growth, and productivity. These two concepts do not always progress in parallel, because high genetic gain does not necessarily translate into economic value. Economic weights convert genetic gain into economic value (Batista et al., 2021). If economic return is not calculated, the true success of plant breeding cannot be measured. Genomic selection has been shown to increase economic gain (Merrick et al., 2022). This relationship is one of the primary reasons for economic optimization. The actual value of genetic advancement is evaluated through economic outcomes; otherwise, plant breeding produces only theoretical progress. Breeding programs not based on economic models lack strategic validity. Thus, plant breeding must be guided by economic thinking. Economic evaluation strengthens alignment between breeding objectives and market needs. In conclusion, modern plant breeding is an interdisciplinary process that integrates genetic progress with economic value.

Cost–benefit analysis (CBA) is a method for assessing plant breeding programs in terms of financial and societal returns. Breeding has been shown to produce benefits far exceeding costs (, 2016). CBA plays a critical role in validating investment decisions. The CAS–CGIAR report reported similar outcomes (CAS–CGIAR, 2020). Without CBA, the efficiency of breeding investments cannot be determined. CBA reveals which strategies are most advantageous. This approach encompasses not only economic but also social benefits. A well-designed CBA enables decision-makers to guide programs properly. Therefore, CBA is the fundamental control mechanism of breeding management. Breeding systems lacking CBA fall into "economic governance" deficiency. Through CBA, breeding programs are evaluated not by short-term cost but long-term economic contribution. Thus, breeding investment policies are grounded in scientific rationale. In summary, CBA is the strongest analytical tool for measuring the sustainability and societal impact capacity of breeding. The success of modern breeding systems depends on the extent to which CBA is integrated into decision-making processes.

Selection indices enable rational decision-making among multiple traits. When economic indices are used, selection is optimized not only biologically but also economically. Economic indices have been shown to provide clear superiority (Batista et al., 2021). Their use has been reported to enhance economic efficiency (Merrick et al. 2022). This method ensures resource savings. The primary aim is to determine the genotypes that yield the highest economic returns. Selection indices are incomplete without economic weights. Therefore, the index approach is at the core of modern breeding. Selection based on economic indices strengthens strategic breeding philosophy. This approach is fully aligned with economic optimization. Moreover, selection indices objectify scientific decision-making processes. Without an index-based approach, selection often remains at a trial-and-error level. Economic indices allow breeders to combine market requirements with agronomic performance. Thus, the selection process is grounded in both economic and biological reality. In conclusion, economic indices are among the most effective tools systematically strengthening the strategic direction of modern plant breeding.

Genomic selection increases economic efficiency by shortening the breeding cycle. Heffner et al. (2009) demonstrated that genomic selection provides speed and accuracy, while Merrick et al. (2022) confirmed that economic efficiency increases under genomic selection. Shortening the cycle length directly translates into a higher annual economic return. Therefore, genomic selection is not only a biological tool but also an economic instrument. Genomic selection reduces costs, and early selection provides economic advantages. Optimizing program strategy lowers financial risk. Genomic selection must therefore be integrated with economic systems. As the rate of genetic gain increases, the return on investment also rises. Compared with traditional selection methods, this approach offers substantially greater efficiency. The economic benefits of genomic selection have become indispensable for modern breeding programs. Therefore, genomic selection lies at the core of economic breeding.

Economic optimization aims to maximize the efficiency of resource use. Alternative breeding scenarios must be evaluated within an economic model. CAS–CGIAR (2020) showed that data-driven strategies increase economic efficiency. Merrick et al. (2022) demonstrated that early genomic selection is economically superior. Such analyses strengthen investment decisions. Strategic optimization reduces risk. Simulation tools support economic evaluation. Effective decision-support systems increase resource efficiency. Resource allocation should be planned with strategic modeling. Economic optimization is the foundation of breeding governance. Economic modeling enables rational decisions regarding which methods to apply. Optimization enhances sustainability and reduces economic uncertainty. Therefore, economic optimization shifts breeding programs from short-term outcomes toward long-term development goals. The

absence of strategic economic modeling leads to inefficient resource allocation. Consequently, economic optimization is a critical management component ensuring the long-term success of modern breeding systems.

As adoption success increases, economic return grows. The CAS–CGIAR (2020) report clearly demonstrated this relationship, which was also supported by findings from Groenewegen et al. (2016). Genetic progress becomes economic value only when it is adopted. A successful breeding program is adopted by farmers in the field. Economic optimization helps increase adoption rates. If adoption is low, economic return remains limited. Therefore, economic analysis must establish the connection between field performance and market value. Strategic assessments reduce adoption risk. Adoption is the ultimate measure of economic success. Adoption analyses allow breeding outcomes to be evaluated not only biologically but also socioeconomically. When farmers adopt varieties, they gain commercial value. This process contributes to increased national agricultural productivity. Thus, adoption is the concrete indicator of the strategic impact of breeding.

The economics of plant breeding creates macroeconomic, not microeconomic, impacts. Noleppa & Cartsburg (2021) demonstrated that plant breeding in the EU increases production, employment, and welfare. These findings show that plant breeding plays a critical role in national development. Economic optimization enhances societal benefit. Correct economic strategies support sustainable agriculture. The economics of breeding should not be overlooked in development planning. Economic impacts may even influence sectors beyond agriculture. Plant breeding is a development tool. Economic analysis makes this reality visible. Therefore, breeding is a macro-strategic activity. Macroeconomic analyses can evaluate the impacts of breeding investments on national income. Breeding activities support rural development and strengthen regional economies. As economic efficiency increases, food security also strengthens. For this reason, breeding programs should be planned within a national development vision. Linking genetic success to economic outcomes is a fundamental requirement of modern agricultural economics.

Economic optimization has become indispensable in plant breeding (Groenewegen et al., 2016; CAS–CGIAR, 2020; Batista et al., 2021; Merrick et al., 2022). Economically weighted breeding produces more efficient outcomes because target traits are selected in alignment with market demand. Cost–benefit analysis is the foundation of strategic planning and validates investment decisions. Genomic selection must also be implemented from an economic perspective, because shortening the cycle length directly increases annual economic gain. Adoption is the key to economic return, and without field-level dissemination, the value of breeding becomes invisible. Macroeconomic impacts must be considered, because breeding affects not only yield but also employment, food security, and regional development. Without economic analysis, breeding remains incomplete, as genetic progress alone does not ensure economic sustainability. The breeding programs of the future will manage economics and genetics jointly. This synergy will guarantee the sustainability of scientific advancement. Moreover, economic modeling will enable the prediction of which strategies are most advantageous. Breeding program performance will increasingly be measured not solely by biological improvement but by economic impact. Therefore, economic optimization will become the most important conceptual framework for defining breeding criteria in the future.

4. Conclusion

This study demonstrates that plant breeding is not only a biological process but also an economic, strategic, and managerial activity. The modern breeding paradigm goes beyond genetic advancement and requires integrating investment planning, demand analysis, product profile design, market alignment, and public–private partnerships. Economic optimization, selection indices, cost–benefit analyses, and genomic selection are key mechanisms that increase the financial return on investment (ROI) in breeding. The literature clearly shows (Groenewegen et al., 2016; CAS–CGIAR, 2020; Persley & Anthony, 2017; Bernardo, 2020) that the actual value of genetic progress becomes tangible through adoption and economic impact in the field. Therefore, modern breeding programs have evolved into interdisciplinary systems that integrate biological success with economic value creation.

From a future perspective, demand-led and market-aligned breeding will be fundamental components of national development, food security, and sustainable agriculture. Genomic selection, strategic economic modeling, and stakeholder analysis will accelerate breeding innovation, increase cost efficiency, and expand product adoption. Breeding science now forms a strong bridge between population genetics and economic decision engineering. In this context, the next generation of breeders will not only be genetic specialists but also program managers, investment strategists, and value-chain designers. In conclusion, a modern breeding system centered on economic optimization is an indispensable technological and developmental tool for the sustainability of global agriculture and societal welfare.

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STRATEGIC MANAGEMENT OF PLANT BREEDING IN TÜRKIYE: NATIONAL FRAMEWORK AND INNOVATION ECOSYSTEM

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ABSTRACT

This study approaches plant breeding in Türkiye not merely as field trials but as an integrated strategic system aligned with national development, food security, and green transformation priorities. Based on international frameworks such as FAO, NAPB, and Plant ETP, the study proposes structuring the national plant breeding strategy on four main pillars: (i) a national strategic framework and policy foundation, (ii) institutional organization, funding, and governance, (iii) a national breeding data system, risk and regulatory management, and (iv) international integration and future vision. The current situation reveals that breeding activities are predominantly project-based, fragmented, and short-term; at the national level, stakeholder analysis, genetic resource management, human resource planning, and financial sustainability are not sufficiently institutionalized within a holistic strategy. The proposed model aims to transform breeding into a "learning" and self-updating ecosystem by utilizing instruments such as centralized data infrastructure, measurable key performance indicators (KPIs), public–private partnerships (PPPs), risk management, and regulatory compliance. In conclusion, the article argues that Türkiye can position plant breeding as a backbone of both economic growth and sustainable food systems by integrating its rich genetic resources and scientific capacity with strategic planning, effective governance, and international engagement.

Keywords: National plant breeding strategy; strategic planning; public–private partnership; data infrastructure; risk and regulatory management.

1. Introduction

Türkiye's agricultural sector is rapidly transforming under the pressures of climate change, population increase, market fluctuations, and food security challenges. These pressures have elevated plant breeding from a biological effort aimed merely at yield improvement to a strategic domain with economic, institutional, and policy dimensions. To remain nationally competitive, adapt to climate risks, and establish sustainable food systems, breeding programs must move beyond sporadic or solely project-based initiatives. Instead, there is a necessity for an integrated "national breeding strategic framework" characterized by a clear vision, defined priorities, stakeholder roles, and accountability mechanisms. This study discusses the strategic management of plant breeding in Türkiye and proposes a national-level framework informed by international best practices.

National and institutional strategic plans are not simply "statements of intent"; they are managerial instruments that guide resource allocation, human capacity development, R&D priorities, and investment decisions. FAO's national strategy guidelines, strategic plans of universities and research institutes, and policy documents from platforms such as NAPB and Plant ETP clearly indicate that breeding must be approached beyond conventional trial plots, within a structure defined by institutional organization, funding models, public–private partnerships, and principles of good governance. In the context of Türkiye, these documents highlight the need for an institutional transformation that favors multi-year, multi-stakeholder program designs over short-term, dispersed projects. Therefore, the axis of "institutional structuring, funding, and governance," encompassing both national policies and strategic planning practices of individual institutions, is addressed as a distinct focus area in this article.

The success of modern breeding programs depends not only on the genetic methods employed but also on the quality of the associated data ecosystem, risk management structures, and regulatory frameworks. In environments where genomic, phenotypic, environmental, and market data are not integrated, where monitoring–evaluation (M&E) and key performance indicators (KPIs) are undefined. Where risk and regulatory mechanisms are not adapted to support innovation, scientific potential fails to translate into economic and societal value. For this reason, the third central axis of this study is dedicated to the strategic design of the national breeding data system, risk management, regulatory structure, and M&E mechanisms. The aim is to present a governance model for Türkiye that is both data-driven and adaptive, offering a resilient breeding ecosystem that minimizes economic, biological, and environmental uncertainties.

Plant breeding is increasingly shaped by international collaboration, technology transfer, and dynamics of global competition. Designing Türkiye's breeding system solely within national boundaries is neither feasible nor strategic; integration with CGIAR, FAO, European technology platforms, regional research networks, and multinational funding mechanisms is imperative. Accordingly, the fourth axis of the article discusses international integration, opportunities for global collaboration, and Türkiye's long-term "breeding vision." The goal is to link the national strategy to a future-oriented perspective that balances scientific capacity, economic return, and sustainability, positioning Türkiye as a regional hub for breeding and phenotyping. In doing so, the study seeks to present a coherent, applicable, and internationally aligned strategic framework for plant breeding in Türkiye across four key pillars.

2. National Strategic Framework and Policy Foundation

Türkiye's agricultural sector is rapidly transforming under the pressures of climate change, population growth, and food security demands. This transformation requires breeding programs

to evolve from purely biological progress toward systems that also target economic, institutional, and strategic outcomes. FAO's (2014) national strategy development guidelines explicitly state that countries must manage genetic resource utilization through structured and stakeholder-based mechanisms. In Türkiye, institutional planning for plant breeding remains fragmented and project-driven; therefore, a national framework is essential. The CUCALS (2020) Strategic Plan presents a strong model for developing a long-term vision, defining measurable goals, and tracking performance indicators. This approach may serve as a reference for strengthening harmonization, coordination, and data sharing among breeding institutions in Türkiye. The NAPB (2024) strategic plan emphasizes that a breeder is not merely a generator of scientific knowledge, but also a resource manager and program designer. The sustainability of breeding programs in Türkiye can be strengthened by institutional strategy frameworks integrating funding and capacity management. The Plant ETP (2023) report demonstrates that investments in breeding in Europe are treated as "strategic" because they fundamentally shape agricultural futures. Türkiye could adopt this perspective to redesign national agricultural policies around a "breeding-centered" approach. Lusser et al. (2011) highlight that commercialization of new breeding technologies requires an appropriate policy framework; this finding is highly relevant for Türkiye in the context of biotechnology-driven breeding. Thus, strategic vision, institutional coordination, and innovation management form the core components of a national breeding strategy in Türkiye. Long-term planning and policy alignment will create the opportunity to transform biological progress into economic growth.

In designing a national breeding strategy for Türkiye, the four pillars proposed by FAO (2014) should be considered: stakeholder analysis, genetic resource management, capacity assessment, and an actionable implementation plan. At present, Türkiye faces challenges in articulating strategic priorities due to the lack of institutional stakeholder mapping. Applying the FAO model could enhance transparency and accountability in breeding programs. The CUCALS (2020) Strategic Plan stresses that strategic documents should not only define vision but also serve as "management tools." In Türkiye, strategic documents must therefore encompass resource allocation, personnel planning, and performance monitoring processes. As shown in the NAPB (2024) plan, education and capacity development constitute integral parts of the strategy. To mitigate the decline in the breeder workforce in Türkiye, strategic planning must invest in training and the development of technical competencies. The Plant ETP report highlights the catalytic role of public–private partnerships in funding; Türkiye's national framework should actively encourage such cooperation. Lusser et al. (2011) demonstrate that commercialization of new breeding technologies becomes feasible when supported by policy. Accordingly, national strategy documents in Türkiye must incorporate regulatory, licensing, and innovation-incentive components. In conclusion, Türkiye should formulate a national strategy that goes beyond biological goals and also covers institutional and economic planning. This approach will reinforce the long-term sustainability of breeding.

The success of strategic documents is directly related to stakeholder analysis and institutional alignment. FAO (2014) notes that stakeholder mapping must be the cornerstone of all breeding activities. In Türkiye, stakeholders include universities, research institutes, private companies, public agencies, producer organizations, and seed firms. These groups must not merely implement the strategy but also shape it. In the CUCALS (2020) Strategic Plan model, stakeholder dialogue is executed systematically, and feedback mechanisms are incorporated into scientific outputs. Institutionalizing such a system in Türkiye would improve the feasibility and adaptability of breeding strategies. The NAPB (2024) document emphasizes that science–policy interaction should be bidirectional. Türkiye's strategic documents must bridge the gap between policymakers and scientists. The Plant ETP (2023) workshop report stresses that

investment strategies require multi-stakeholder platforms; Türkiye could adapt this model. Lusser et al. (2011) show that policy–research interaction accelerates regulatory success. Therefore, institutional alignment is the most critical component of Türkiye's strategy. Strong institutional coherence reduces resource wastage, prevents duplication of effort, and enhances performance. For this reason, the national strategy must define roles and responsibilities across stakeholders. In summary, stakeholder-based institutional harmonization is the fundamental element securing the sustainability of Türkiye's breeding strategy.

Türkiye possesses significant plant genetic resources due to its substantial ecological diversity; however, the strategic utilization of these resources has not yet been defined at the institutional level. FAO (2014) guidelines state that genetic resources must be prioritized within the national strategy and managed with long-term objectives in mind. Gene banks in Türkiye provide essential inputs to breeding programs, yet data-sharing infrastructure remains inadequate. The CUCALS (2020) Strategic Plan emphasizes the importance of a centralized genetic resource database; this approach should be adopted in Türkiye. The NAPB (2024) document stresses that genetic resources should be managed on a system basis, not a project basis. In Türkiye, a lack of policy-level coordination in genetic resource management reduces efficiency. The Plant ETP (2023) report shows that investments in genetic resources in Europe are considered "strategic infrastructure investments." In Türkiye, long-term goals for the utilization of genetic resources must be defined within a national strategic framework. Lusser et al. (2011) argue that new breeding technologies cannot be considered independently from genetic resource management; this insight is vital for Türkiye's modern breeding dynamics. The transfer of genetic resources into commercial varieties underpins sustainable breeding. Data integration between genetic resource programs and breeding projects has become essential in Türkiye. Achieving this integration will enhance both environmental and economic efficiency of the breeding system. An appropriate genetic resource strategy will also reinforce the goals of quality, adaptation, and market suitability. Therefore, genetic resource management represents a critical component of the national plan.

Current breeding efforts in Türkiye are primarily conducted as Research and Development (R&D) projects but are not embedded within a national innovation management framework. FAO (2014) stresses that strategic documents must analyze innovation capacity; in Türkiye, such analysis is not yet systematically implemented. The CUCALS (2020) Strategic Plan shows that innovation is connected to robust institutional architecture and risk management. The NAPB (2024) plan positions innovation within both technical and economic dimensions; in Türkiye, economic returns of innovation are not yet clearly defined. The Plant ETP (2023) report indicates that strategic financing mechanisms must support breeding innovation. Türkiye currently lacks such financing models; this weakens long-term breeding projects. Lusser et al. (2011) demonstrate that commercialization cannot occur without policy support. Türkiye's national strategy must therefore include the commercialization dimension of innovation. Prioritization mechanisms must be established to translate R&D outputs into products. Without innovation management, the effectiveness of technological breeding methods remains limited. Performance indicators measuring the economic impact of R&D should be developed. R&D outputs should be aligned with product profiling and feasibility considerations. Thus, innovation and R&D management must form the backbone of the national breeding strategy.

3. Institutional Architecture, Funding, and Governance

The FAO (2014) guidelines emphasize that financial sustainability must be addressed in strategic planning; however, Türkiye's current funding model remains project-based rather than strategic. The CUCALS (2020) Strategic Plan demonstrates that public–private partnerships

increase the efficiency of R&D. NAPB (2024) defines public–private sector collaboration as the driving force of breeding growth. The Plant ETP (2023) report states that breeding investments should be classified as “national strategic investments.” Türkiye should likewise elevate breeding investments to a strategic category. Lusser et al. (2011) show that commercialization of new breeding approaches accelerates when supported by financial incentives. Such an incentive mechanism has not yet been established in Türkiye. Policy instruments must be developed to encourage private-sector R&D investment. National strategy funds must support the full length of the breeding cycle. Program financing should be based on multi-year planning rather than annual budgeting. Public–private partnership models will strengthen data-sharing and risk management. Without financial sustainability, breeding success cannot be durable. The national strategy should incorporate funding diversity and risk analysis of financing. This will enhance the investability of the breeding system in Türkiye.

The breeder workforce in Türkiye is aging and declining in numbers, representing a strategic risk. FAO (2014) explicitly emphasizes that the human resources component must be a core element of strategic documents. The CUCALS (2020) Strategic Plan places educational vision at the center of breeding strategy, which is a valuable model for Türkiye. NAPB (2024) advocates simultaneous development of technical and managerial competencies among breeders. Breeding education in Türkiye is mainly academic, and professional governance capabilities are insufficiently cultivated. Plant ETP (2023) shows that hybrid education models have been developed in Europe to expand breeding capacity. Turkish education platforms should likewise operate beyond universities and incorporate industry collaboration. Lusser et al. (2011) indicate that technical expertise is a decisive factor in innovation speed. A breeding system without a human resource strategy cannot be sustainable. Educational programs must target long-term capacity building. Technical expertise should encompass data analytics, genomics, quality control, and economic assessment. Türkiye's national strategy should support interdisciplinary training models. Capacity development must be monitored through measurable performance indicators. In summary, human resource strategy is the most critical factor determining the future of the breeding system.

The success of national breeding programs can only be evaluated through measurable Key Performance Indicators (KPIs). FAO (2014) clearly emphasizes that strategic plans must incorporate monitoring and evaluation mechanisms. The KPI structure in the CUCALS (2020) Strategic Plan includes metrics such as publication outputs, variety registration, technology transfer, adoption rates, and economic impact. NAPB (2024) mandates annual KPI reporting for the U.S. breeding system. The Plant ETP (2023) workshop report recommends monitoring economic performance indicators to assess returns on breeding investments in Europe. In Türkiye, KPIs are mostly reported at the project level, making system-wide performance assessment impossible. Properly designed KPIs serve as enforcement tools for strategic alignment. Lusser et al. (2011) demonstrate that new breeding techniques are adopted more rapidly when evaluated by economic performance indicators. Establishing species- and approach-based KPI systems is therefore essential for Türkiye. KPIs also generate critical data for investment prioritization. Governance cannot be effective without KPIs. When strategic evaluation is indicator-based, transparency increases. Regular reporting of monitoring and evaluation results contributes to the sustainability of the national strategy. Therefore, KPI systems must cover not only technical performance but also economic, social, adoption, and commercialization dimensions.

Breeding data in Türkiye are dispersed across separate projects, and the absence of a national data infrastructure weakens decision-making. FAO (2014) states that genetic resources should be supported through centralized data management. The CUCALS (2020) Strategic Plan

classifies data integration as “institutional strategic infrastructure.” NAPB (2024) recommends shared digital platforms for breeding data management in the U.S. The Plant ETP (2023) report shows that data architecture determines the speed of green transformation and innovation in Europe. Establishing data management structures in Türkiye will accelerate innovation, prevent duplication of effort, and enhance economic efficiency. Lusser et al. (2011) indicate that effective data management enhances the utility of new breeding approaches. Data systems must integrate genomic, phenotypic, environmental, and market information. Centralized data storage represents a critical infrastructure from a strategic governance perspective. Without data infrastructure, AI-driven and model-based breeding cannot be implemented. Strategic planning must define data security and access protocols. When operated at the national scale, data infrastructure will accelerate public–private cooperation. Implementation of a national data management strategy will enhance Türkiye’s international competitiveness in breeding.

Risk management constitutes the intersection of all strategic planning dimensions in a national breeding strategy. FAO (2014) states that risk analysis must be embedded in strategic documents. The CUCALS (2020) Strategic Plan characterizes risk management as essential for sustaining success. NAPB (2024) proposes decision-support systems to analyze financial, biological, market, and climate risks. The Plant ETP (2023) report recommends planning risk management at the national policy level. In Türkiye, risk assessment is conducted at the project level but remains underdeveloped. Lusser et al. (2011) show that perceived risk slows commercialization of new techniques; therefore, risk management communication is essential. Strategic risk planning must be defined across species, target environment, and time dimensions. Decision-support systems should incorporate econometric models, yield forecasting systems, and risk simulations. Without risk management, resource waste increases and program success declines. Strategic risk evaluation mechanisms must be institutionalized in Türkiye. Risk management should be linked to KPI monitoring. The strategic plan must include tools for risk prediction and mitigation. Through this approach, the national breeding system becomes strong, resilient, and predictable.

4. National Breeding Data System, Risk, and Regulatory Governance

The success of a national strategy depends on aligning scientific research outputs with policy and industry. FAO (2014) argues that multi-stakeholder integration must be defined within strategic documents. The CUCALS (2020) Strategic Plan identifies science–industry collaboration as the primary determinant of innovation speed. NAPB (2024) regards policy–science coordination as an essential prerequisite for a national breeding ecosystem. Plant ETP (2023) shows that policy integration strengthens funding decisions across Europe. In Türkiye, policy documents are often disconnected from scientific strategies, resulting in efficiency losses. Lusser et al. (2011) demonstrate that technological innovation becomes widespread only when policy support is present. When scientific research is aligned with policy objectives, commercialization accelerates. Industry–R&D collaborations shorten product development cycles. The national strategy must explicitly define the multi-stakeholder coordination structure. Sustainable financing cannot be achieved without policy integration. In Türkiye, sustainable agriculture goals must be embedded into the breeding strategy. Alignment between policy and science enhances economic and societal return. Thus, integration constitutes a critical building block for the long-term success of the breeding system.

A national breeding strategy must include an innovation framework that systematically guides R&D activities. FAO (2014) emphasizes that innovation is not only a scientific output but also a concrete component of policy and investment planning. The CUCALS (2020) Strategic Plan describes innovation-oriented R&D as the “core source of institutional competitive advantage.”

NAPB (2024) seeks to enhance innovation adoption by aligning R&D strategies with market needs. The Plant ETP (2023) report reveals that innovation functions as a strategic lever for green transformation and climate resilience. In Türkiye, innovation remains largely project-based and lacks strategic national positioning. Lusser et al. (2011) show that commercialization of new technologies (genome editing, marker-assisted selection, phenotyping technologies) accelerates when embedded within innovation systems. The national strategy must integrate breeding innovations with biotechnology, data science, agroecology, and industrial bioprocesses. For the R&D ecosystem to function effectively, infrastructure, human resources, and funding mechanisms must be addressed simultaneously. The innovation ecosystem must generate outcomes beyond scientific publications, including technology transfer, commercialization, patent portfolios, product development, and industrial application. Strategic direction is required for Türkiye's innovations to contribute to an international patent portfolio. The national innovation architecture should be supported by open innovation and pre-competitive collaboration principles. These structural arrangements will strengthen Türkiye's position in the global breeding innovation landscape.

Public–private partnerships (PPP) constitute one of the primary leverage mechanisms within breeding strategies. FAO (2014) emphasizes that public–private integration is critical for genetic resource management. The CUCALS (2020) Strategic Plan treats collaboration between the private sector and universities as a mandatory structural component. NAPB (2024) demonstrates that PPP models improve funding efficiency in the U.S. breeding system. Plant ETP (2023) provides strong evidence that PPP accelerates investment returns and commercialization success in Europe. In Türkiye, PPP effectiveness remains limited due to the absence of a strategic framework. Lusser et al. (2011) stress that sector–science integration is essential for the commercialization of new techniques. PPP provides not only financial resources but also knowledge transfer, infrastructure sharing, and technological inclusiveness. Public strengths (risk management, research capacity, regulatory support) must be combined with private strengths (market access, commercialization speed, product design). Without a strategic PPP model, the national innovation chain remains fragile. PPP structures in Türkiye can generate both technical and economic leverage within breeding projects. The strategic plan must define clear procedures, incentive mechanisms, and investment models for PPP. Such a model will support long-term sustainable agriculture, enhance food security, and institutionalize the innovation ecosystem.

The success of the national breeding strategy is directly linked to financial sustainability. FAO (2014) argues that financial planning must be clearly articulated in strategic documents. The CUCALS (2020) Strategic Plan identifies funding as a "critical determinant" of program efficiency. NAPB (2024) reports that U.S. funding strategies are prioritized according to target species, innovation areas, and societal needs. Plant ETP (2023) shows that breeding finance in Europe is directed through strategic investments. In Türkiye, funding remains project-based mainly; therefore, system-level strategic impact is limited. Lusser et al. (2011) demonstrate that commercialization cannot be achieved without adequate funding for new technologies. The national funding model must support both fundamental and applied research. Funding should be directed by KPI performance and be outcome-oriented. Strategic investments should consider long-term evaluation, economic impact analysis, and commercialization potential. Redesigning the funding system in Türkiye requires prioritization, clear metrics, and transparency in evaluation. International funds (Horizon Europe, CGIAR, ERANET) must be harmonized with national strategic goals. Funding should support innovation centers, data platforms, and advanced phenotyping infrastructure. Financial sustainability constitutes the backbone of the strategic plan.

Human resources constitute the most critical structural element of breeding strategies. FAO (2014) emphasizes that human resource planning in national strategies must incorporate long-term foresight. The CUCALS (2020) Strategic Plan frames capacity development as a "pillar of institutional sustainability." NAPB (2024) places educational development, on-the-job learning, certification programs, and leadership training as a strategic phase. Plant ETP (2023) shows that human resource strategies in Europe play a decisive role in the adoption of new technologies. In Türkiye, human resource strategies remain unsystematic and dependent on individual initiatives. Lusser et al. (2011) demonstrate that the success of new technologies is directly linked to the level of expertise. The national strategy must target integrated education across genomics, bioinformatics, phenotyping, protein processing, quality analysis, data science, and economics. Long-term capacity planning must include components for graduate education, farmer training, and technology transfer. Human resource development must be supported through PPP structures. Institutional mentorship and international exchange programs will provide strategic impact. A national "Plant Breeding Academy" model could be established in Türkiye. Without incorporating talent development into the strategy, the long-term success of breeding programs cannot be achieved. Therefore, human resource governance must remain a central component of the strategic plan.

5. International Integration and Future Vision

A modern component of strategic breeding programs is data management and digital infrastructure. FAO (2014) indicates that national strategies must treat data infrastructures as central functions. The CUCALS (2020) Strategic Plan positions data management as a mechanism of "institutional intelligence." NAPB (2024) demonstrates that integrating phenotypic, genetic, and environmental data increases program efficiency in the United States. Plant ETP (2023) reports that data infrastructure investments in Europe align with green transformation and sustainable breeding goals. In Türkiye, data infrastructure is project-based mainly and lacks national system integration. Lusser et al. (2011) point out that an effective digital ecosystem is indispensable for implementing new breeding techniques. A national data platform must capture seed systems, phenotypic analyses, genomic datasets, and adaptation performance. Without data integration, economic optimization and risk management are not possible. Data security and open-access principles should function as dual pillars of the strategic plan. The digital platform should incorporate machine learning, simulation models, and decision-support systems. A national "Breeding Data Institute" model could be established. Data sharing should be structured to support access by researchers, private-sector stakeholders, and policymakers. Integration into international data platforms will enhance Türkiye's competitiveness. Without digital infrastructure, the breeding strategy will not withstand global competition.

The effectiveness of a national breeding strategy depends on its legal (TCRG, 2004; 2006) framework and governance model. FAO (2014) shows that participatory governance enhances stakeholder alignment. The CUCALS (2020) Strategic Plan integrates governance with the monitoring and evaluation cycle. NAPB (2024) highlights that governance is the mechanism determining the accuracy of strategic investment decisions. Plant ETP (2023) notes that governance is essential for the efficiency of green transformation investments across Europe. In Türkiye, the legal framework is robust regarding seed systems, yet insufficiently systematic for breeding strategy. Lusser et al. (2011) show that regulatory adaptation is necessary for the commercialization of new technologies. The national governance model should rely on transparency, accountability, performance metrics, and participatory decision-making. Regulation must balance risk management and innovation. Overly strict regulations slow down innovation, while overly lax regulations jeopardize quality; thus, a strategic balance model is

required. Regulatory design must be harmonized with PPP structures. Governance must systematically measure economic impacts. A national coordination unit should be established. Without regulatory modernization, the breeding strategy will not yield a global competitive advantage.

The sustainability of the strategic plan depends on the monitoring and evaluation (M&E) system. FAO (2014) states that M&E is a critical component of strategic performance assessment. The CUCALS (2020) Strategic Plan employs KPI (Key Performance Indicator) models for institutional decision-making. NAPB (2024) shows that strategic funding in the U.S. breeding system cannot function effectively without M&E. Plant ETP (2023) reports that M&E outputs are decisive in investment planning across Europe. In Türkiye, M&E structures are limited and not integrated into strategic decision-making. Lusser et al. (2011) indicate that performance evaluation of new techniques predicts commercialization success. The M&E system must measure both biological and economic performance. Performance indicators should include genetic gain, financial return, adoption rate, environmental impact, and speed of commercialization. KPI definitions must be embedded in the strategic plan. The M&E system must be data-driven. A national M&E platform should produce annual reports. Monitoring should measure not only performance but also risk. Success indicators must be internationally comparable. M&E constitutes the foundation of the strategic plan's "learning system" model.

A national strategy cannot function at full capacity without international integration. FAO (2014) emphasizes the strengthening effects of international cooperation—the CUCALS (2020) Strategic Plan positions global partnerships as scientific force multipliers. NAPB (2024) identifies international networks as vital for education and technology transfer in the U.S. Plant ETP (2023) shows that breeding innovation in Europe cannot accelerate without global cooperation. Türkiye is open to global strategic cooperation but lacks a systematic model. Lusser et al. (2011) report that new techniques cannot be optimally utilized without international technology exchange. Global cooperation provides funding, infrastructure, data sharing, and expertise transfer. Strategic partnerships should be developed with CGIAR, FAO, ICARDA, and ERANET. International licensing arrangements enhance knowledge transfer. Türkiye could emerge as a regional innovation hub. International cooperation creates opportunities for regulatory benchmarking. Global positioning increases competitiveness. The strategic plan may position Türkiye as a "regional breeding and phenotyping center." This approach ensures long-term sustainability.

The ultimate aim of the strategic plan is to translate scientific progress into economic, social, and environmental benefits. FAO (2014) states that vision must align with national development goals. The Cornell Strategic Plan defines vision as "institutional sustainability and global leadership." NAPB (2024–2029) demonstrates that strategic vision elevates the breeder's role to that of a decision manager. Plant ETP (2023) notes that strategic vision must produce societal welfare, not just technical advancements. For Türkiye, the vision is equilibrium between "scientific capacity + economic return + sustainable agriculture." Lusser et al. (2011) report that new techniques create tangible economic impact when supported by the right strategic vision. The national vision must rely on strong human resources, effective R&D, sustainable funding, and digital data infrastructure. The vision must target not only laboratory success but also the development of varieties adopted at the field level. Economic and socio-economic impacts must be central. Türkiye may become a regional leader in sustainable protein resources and adaptive farming systems. The vision must promote alignment among stakeholders. The success of the vision depends on performance-monitoring and outcome-evaluation systems. Strategic vision can position Türkiye as a global actor in breeding innovation.

5. Conclusion

This study demonstrates that plant breeding in Türkiye should no longer be treated merely as a biological process confined to field trials, but rather as a strategic system directly linked with national development, food security, and green transformation objectives. Analyses of international frameworks such as FAO, NAPB, Cornell, and Plant ETP reveal that the common denominator among successful countries includes the presence of clear national strategic plans, institutional alignment, robust data infrastructure, and multi-stakeholder governance. When Türkiye's existing scientific capacity and rich genetic resources are integrated into such a strategic configuration, significant advantages can be achieved in terms of climate-resilient cultivar development, sustainable protein supply, and a competitive seed sector.

The proposed four pillars—(i) national strategic framework and policy foundation, (ii) institutional architecture, funding, and governance, (iii) national breeding data system, risk and regulatory management, and (iv) international integration and future vision—jointly enable the design of a holistic "breeding ecosystem" for Türkiye. Within this ecosystem, the breeder evolves from a generator of genetic gain into a program leader and strategic decision-maker who simultaneously manages economic returns, adoption dynamics, environmental sustainability, and societal impact. National-level data platforms, performance indicators, PPP models, and international collaboration networks will transform breeding programs from short-term projects into multi-year, continuously improving development instruments.

In conclusion, Türkiye's primary opportunity lies in leveraging its scientific expertise and rich genetic diversity through a well-designed strategic framework to position plant breeding as a backbone for both economic growth and sustainable food systems.

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MINERAL CONTENT, ANTIOXIDANT ACTIVITY AND BIOACTIVE COMPOUNDS OF FENNEL (*Foeniculum vulgare*) GROWN UNDER THE ECOLOGICAL CONDITIONS OF KONYA

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ABSTRACT

Fennel (*Foeniculum vulgare*) is a medicinal and aromatic plant that is widely used in the food, pharmaceutical and cosmetic industries. In this study, it was aimed to determine the mineral content of fennel seeds cultivated under the ecological conditions of Konya, as well as the antioxidant activity and bioactive components in seed extracts. Fennel seeds were found to be rich in the minerals potassium, calcium and phosphorus. The antioxidant activity of the extracts obtained from the seeds was determined as 0.019 ± 0.001 mg TE/mL, and the bioactive components were identified as anethole, p-anisyl acetone, oleic acid and linoleic acid. The results indicate that fennel seeds can be evaluated as a natural raw material in functional foods, nutraceuticals and pharmaceutical applications.

Keywords: Fennel, *Foeniculum vulgare*, mineral content, antioxidant activity

1. INTRODUCTION

Fennel (*Foeniculum vulgare*) is one of the oldest cultivated plants, belonging to the Apiaceae family, herbaceous in nature and capable of growing 1-1.5 m in height. There is evidence that it was used for medicinal purposes by the Sumerians, Ancient Egyptians and Ancient Greeks as early as 3000 BC (Zeybek and Haksel, 2010). While the bulb, young shoots, leaves and dried fruits of the fennel plant are used in traditional remedies, its aromatic fruits are utilized as a spice (Tanira et al., 1996). In addition, teas containing fennel seeds are traditionally consumed in Europe and Asia for digestive and respiratory ailments (Raffo et al., 2011). Although the plant originates from the Mediterranean and Western Asia, it is now widely cultivated in warm and temperate regions (Badgujar et al., 2014). In Türkiye, it is commonly found in the Aegean and Mediterranean regions (Zeybek and Haksel, 2010), and is cultivated in the provinces of Afyonkarahisar, Ankara, Konya, Antalya and Burdur (TUIK, 2025).

Worldwide, two main varieties of fennel are cultivated: bitter fennel (*Foeniculum vulgare* var. *vulgare*) and sweet fennel (*Foeniculum vulgare* var. *dulce*) (Zeybek and Haksel, 2010). In Türkiye, however, all cultivated fennel types belong to sweet fennel (var. *dulce*). Sweet fennel, which is generally an annual and occasionally a biennial plant, is particularly important because its seeds are used as a spice (Baydar, 2016). In Türkiye, fennel is known by various local names such as “arapsaçı, meletüre, irziyan, mayana, razıyane, cumhur, çumra, ısıra, sincibil, sincilip, rezdene, sarı ot” In English, it is referred to by names such as “anise, aniseed, aniseed weed, bitter fennel, common fennel, Florence fennel, Roman fennel, sweet anise and sweet fennel” (Duke, 2002).

In several studies conducted in Türkiye, trans-anethole has been reported as the main constituent of the essential oil obtained from Turkish fennel (Coban et al., 2018; Telci et al., 2019), whereas other investigations have identified methyl chavicol as the predominant component (Özcan and Akgül, 2001; Özcan and Chalchat, 2006). Furthermore, Katar et al. (2021) reported that methyl chavicol is the principal constituent of the essential oils in different organs of fennel, except for the leaves.

Mineral elements not only determine the nutritional value of plants but also influence their functional properties by exhibiting synergistic interactions with bioactive compounds. It has been reported that fennel seeds contain approximately 13-14% mineral matter and that these mineral components include essential elements such as calcium, potassium, sodium, magnesium, phosphorus and iron, as well as trace amounts of zinc and manganese (Rather et al., 2016). However, studies on the mineral content of fennel grown in Türkiye are quite limited, which highlights the importance of elucidating the mineral composition of this species under local ecological conditions.

This study was conducted to determine the mineral contents of fennel seeds grown in the Çeltik district of Konya province, to evaluate the antioxidant activity in the obtained extracts, and to identify the bioactive compounds present in these extracts. The data to be obtained are expected to contribute to the evaluation of fennel as a functional food ingredient and a natural source of antioxidants.

2. MATERIALS VE METHODS

In this study, fennel (*Foeniculum vulgare* var. *dulce*) seeds were used as the material. The field trials were carried out during the 2024 summer growing season in İshakuşağı village, Çeltik district of Konya province. The study area is characterized by a semi-arid continental climate. The soil in which fennel was cultivated is loamy and partially calcareous, with a depth of 50 cm, a lime content of 25%, an organic matter content of 2-3%, and an average pH of 7.1. Fennel

cultivated under farmer conditions was sown on 12/04/2024 and harvested on 20/08/2024. After harvest, foreign materials (stems, leaves, dust, etc.) were removed from the seeds, which were then prepared for analysis.

2.1. Preparation for analysis and extract yield

For the preliminary preparation for analysis and extract yield determination, 10 g of fennel seeds were ground and macerated with 200 mL of solvent (70% ethanol-water mixture) on a shaker at room temperature for 48 h. The organic solvents were removed by evaporation under reduced pressure, and the extract yield (%) was calculated.

2.2. Mineral contents

Seed samples were digested by microwave (HNO_3 and H_2O_2, 210°C, 200 PSI), diluted to 20 mL, and mineral analyses (B, Ca, Cu, Fe, K, Mg, Mn, Na, P, S, Zn) were performed by ICP-OES according to the method of Tošić et al. (2015); results were reported in ppm.

2.3. Antioxidant activity

DPPH (1,1-diphenyl-2-picrylhydrazyl) radical scavenging activity was measured by monitoring absorbance at 517 nm, after 30-minute incubations at room temperature in the dark, was conducted in accordance with Grochowski et al. (2017). Results were expressed as mg trolox equivalents (mg TE/mL extract).

2.4. GC-MS Analysis

GC-MS analyses were carried out using a Shimadzu QP2010 Ultra GC-MS system. Mass spectra were scanned in the 50–550 m/z range, and compounds were identified using the NIST library.GC operating conditions were as follows: column oven temperature 240 °C, injection temperature 250 °C. The injection mode was split with a split ratio of 1:10, and the sampling time was 1.00 min. The flow control mode was pressure-controlled, with a system pressure of 83.5 kPa. The total flow was 19.5 mL/min. Helium was used as the carrier gas, with a column flow rate of 1.50 mL/min and a linear velocity of 44.2 cm/s. The purge flow (split) was 3.0 mL/min. Computer matching against commercial libraries (Wiley GC–MS Library, Adams Library, MassFinder 3 Library) as well as MS literature data was used for the identification of essential oil components (European Pharmacopoeia, 2011).

3. RESULTS AND DISCUSSION

3.1. Extract Yield

Extract yield (%) indicates how efficiently a solvent can remove useful components from plant or seed material. This value provides information about the active compounds, nutritional value, and pharmacological effects of plant products (Adam et al., 2019). The extract yield of fennel seeds was determined as 8.6 ± 0.1%, showing that fennel seeds can be regarded as a promising source of extractable bioactive constituents. In the study conducted by Anwar et al. (2009), the highest extract yield was reported with 80% ethanol (15.63%), while the lowest yield was obtained with 100% methanol (6.21%). The extract yield obtained in the present study falls within the range reported by Anwar et al. (2009), indicating that differences in extract yield may arise from methodological factors such as the type and concentration of solvent, solid-to-solvent ratio, extraction time and temperature, as well as from variations in plant genotype and growing conditions.

3.2. Mineral contents

In fennel seeds, the macro elements phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) were determined as 141.45 ± 0.68, 382.54 ± 1.17, 292.56 ± 1.17 and 0.55 ± 0.01 ppm, respectively. Among the micro elements, sodium (Na), iron (Fe), zinc (Zn), copper (Cu), manganese (Mn) and boron (B) contents were measured as 3.99 ± 0.01, 1.99 ± 0.01, 0.70 ± 0.01, 0.54 ± 0.02, 0.99 ± 0.01 and 0.99 ± 0.01 ppm, respectively (Table 1). These results indicate that fennel seeds are particularly rich in K and Ca among the macro elements and contain measurable amounts of essential trace elements such as Fe, Zn, Cu, Mn and B, which contribute to their potential nutritional value. Endalamaw and Chandravanshi (2015) reported calcium, magnesium, iron, manganese, copper and zinc contents in fennel fruits in the ranges of 20500-23000 µg/g, 1310-3460 µg/g, 1140-1900 µg/g, 31-51 µg/g, 24-103 µg/g and 37-45 µg/g, respectively. In another study, Başgel et al. (2006) determined calcium, magnesium, iron, manganese, copper and zinc contents in fennel seeds as 10780 ppm, 2774 ppm, 224.8 ppm, 27.8 ppm, 16.2 ppm and 37.0 ppm, respectively. Potassium is a vital intracellular mineral, crucial for osmotic balance and metabolic processes like energy transduction and protein synthesis (EFSA NDA Panel, 2016). Calcium, a key skeletal component, also functions as an essential intracellular messenger (EFSA NDA Panel, 2015). Therefore, the high levels of potassium and calcium found in fennel seeds suggest that this plant may represent a valuable mineral source from a nutritional point of view.

Table 1. Macro, micro elements of fennel seeds (Mean±SD)

Macro Elements (ppm)		**Micro Elements (ppm)**	
P	141.45±0.68	Na	3.99±0.01
K	382.54±1.17	Fe	1.99±0.01
Ca	292.56±1.17	Zn	0.70±0.01
Mg	0.55±0.01	Cu	0.54±0.02
		Mn	0.99±0.01
		B	0.99±0.01

3.3. Antioxidant activity

Based on the DPPH radical scavenging assay, the antioxidant activity of the fennel seed extracts was measured as 0.019 ± 0.001 mg TE/mL. These findings indicate that fennel seeds possess a noticeable antioxidant potential. Anwar et al. (2009) reported the DPPH radical scavenging activity of fennel seed essential oil and different solvent extracts as IC_{50} values of 32.32 µg/mL and 23.61–26.75 µg/mL, respectively. The differences between our DPPH radical scavenging values and those reported by Anwar et al. (2009) may be attributed to several factors, including the type of extract (seed extract vs. essential oil), the extraction solvent and conditions, the way antioxidant activity is expressed (mg TE/mL vs. IC_{50} in µg/mL), as well as possible variations in genotype, growing environment, harvest time and storage conditions of the fennel seeds.

3.4. Bioactive compounds in the extract

The main bioactive compounds detected in the fennel seed extract were anethole (1.72%), p-anisyl acetone (1.18%), oleic acid (2.84%) and linoleic acid (2.01%). Anethole and p-anisyl

acetone are essential oil components, whereas oleic acid and linoleic acid are unsaturated fatty acids.

Anethole, one of the major essential oil components of fennel seeds, is known as the principal contributor to the characteristic sweet and spicy aroma of fennel, and has been reported to possess antimicrobial, anti-inflammatory, antispasmodic and antioxidant properties (Marinov and Valcheva-Kuzmanova, 2015). The aromatic compound p-anisyl acetone has been identified as one of the main antibacterial agents (Yang et al., 2021). In addition, the presence of the unsaturated fatty acids oleic acid and linoleic acid, which are considered key constituents, may contribute to the antioxidant and anti-inflammatory potential of the extract. These findings indicate that fennel seed extract contains both volatile and fixed oil components and therefore may be utilized in the food and health sectors.

4. CONCLUSIONS

The study showed that fennel seeds are rich in essential minerals, particularly potassium, calcium and phosphorus, and that they contain notable bioactive compounds such as anethole, p-anisyl acetone, oleic acid and linoleic acid, together with a measurable antioxidant activity (0.019 ± 0.001 mg TE/mL). These bioactive compounds are associated with antimicrobial, antioxidant and antiinflammatory effects. Therefore, it can be concluded that fennel seeds grown under the conditions of Konya are valuable not only in terms of flavor and aroma, but also as a natural source of minerals and bioactive compounds; and that their use as a spice offers additional potential for functional food, nutraceutical and pharmaceutical applications. Fennel cultivation in Konya province demonstrates both agricultural suitability and sustainability. Due to its considerable production potential, there is a need to further develop fennel farming in this region. In addition, it is important to investigate and evaluate other species and varieties belonging to the same family in this area in terms of yield and quality, so that they can meet the standards set by global markets.

Conflict of Interest

The authors declare no conflict of interest regarding this study.

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BAZI MERCİMEK GENOTİPLERİNİN TARIMSAL ÖZELLİKLERİNİN BELİRLENMESİ

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ÖZET

Bazı mercimek genotiplerinin Sivas ekolojik koşullarında tarımsal özelliklerinin ortaya konulması amacıyla 2024 yılında tesadüf blokları deneme deseninde dört tekrarlamalı olarak gerçekleştirilen çalışmada 27 adet ileri düzeye kadar getirilmiş mercimek hattı ile 3 adet standart yeşil mercimek çeşidi olmak üzere 30 adet yeşil mercimek genotipi materyal olarak yer almıştır. Yürütülen araştırmada tarımsal özellikler olarak bitki boyu (cm), ilk bakla yüksekliği (cm), biyolojik verim (g), bitkide bakla sayısı (adet), bitkide tane sayısı (adet), bin tane ağırlığı (g), bitkide tane verimi (g) ve hasat indeksi (%) yer almıştır. Çalışma sonucunda yeşil mercimek genotiplerinde 1.84-3.51 g aralığında bitkide tane verim değerleri belirlenmiş olup bitkide tane verimine en yüksek M-14 nolu genotipi sahip olurken en düşük bitkide tane verimi ise M-11 nolu genotipte ortaya konulmuştur. Yine çalışmada yeşil mercimek genotiplerine bağlı olarak bitki boyunda 17.00-30.00 cm, bitkide bakla sayısında 19.00-51.00 adet, bitkide tane sayısında 14.00-55.00 adet ve bin tane ağırlığında 33.47-49.75 g aralığında değerler elde edilmiştir. Sonuç olarak; M-5, M-14, M-15 ve M-31 nolu genotiplerinden elde edilen verim unsurlarına ait değerlerin diğer yeşil mercimek genotiplerine göre daha yüksek oldukları ortaya konulmuştur.

Anahtar Kelimeler: Sivas, Yeşil mercimek, Genotip, Verim, Tarımsal özellikler

1. GİRİŞ

Bir yemeklik tane baklagil bitkisi olan mercimek hem insan hem de hayvan beslemede önemli bir yere sahip olup kültüre alınan en eski yemeklik tane baklagil türlerinden birisidir. Mercimeğin ilk kültüre alındığı yerin verimli yarım ay dediğimiz Mezopotamya ile ülkemizin Güneydoğu Anadolu Bölgesi olduğu tahmin edilmekle beraber (Özdemir, 2002) tarımının yaklaşık olarak günümüzden 8.000 yıl öncesine kadar dayandığı bilinmektedir (Pellet, 1988). Yapılan arkeolojik kazılarda Türkiye'de Hacılar, Çayönü ve Çan Hasanda M.Ö. 7000-6500, Yunanistan'da M.Ö. 6500-6000, Irak, İran ve Ürdün'de M.Ö. 7000-6500 ve Suriye'de ise M.Ö. 8500-7500 yıllarına ait mercimek fosillerinin kalıntılarına saptanmıştır (Sepetoğlu, 2002). Ülkemizde ise Karadeniz Bölgesi'nin doğusu hariç hemen hemen her bölgede yetiştiriciliğinin yapıldığı bilinmektedir (Şehirali, 1988).

Çok uzun yıllardır insan beslenmesinde yoğun bir şekilde kullanılan mercimek; enerji, protein, lif, vitaminler ve mineraller (Na, Cu, K, Mg, P, Ca, Fe, Mn, Zn) bakımından da zengin (Urbano ve ark., 2007) olmasının yanında tohumlarındaki %25 civarında protein içeriği ile baklagiller içerisinde soya fasulyesinden sonra en yüksek proteine sahip baklagil türü konumundadır.

Çözünür lif kaynağının yüksek olmasından dolayı mercimek bitkisinin aynı zamanda kolesterol düşürücü, kan şekerini dengeleyici ve tokluk hissini artırıcı etkileri göstermesi nedeniyle kilo önleyici özelliği de bulunmakta olup çözünür lif kaynağının yüksek olması nedeniyle kan çözünmez lif içeriği sayesinde kabızlığı önleyerek sindirim sistemi rahatsızlıklarının giderilmesine de yardımcı olduğu belirlenmiştir (Rehinan ve ark., 2004).

Tek yıllık vejetasyona sahip olan mercimek; soğuğa, kurağa ve yüksek sıcaklıklara dayanıklılık göstermesinin yanında toprak isteği bakımından fazla seçici olmamasından dolayı kuru tarım alanlarında bir tahıl bitkisi olan buğday ya da arpa ile ekim nöbetine girmekte olup insanların ve hayvanların beslenmesindeki öneminin yanında toprak verimliliğine olumlu katkısı ve yüksek kazanç getirisiyle tarımsal bakımdan çok önemli bir konumda bulunmaktadır. Hasat ve harman sonra geriye kalan sap/samanda çok az miktarda da olsa selüloz bulunabildiğinden hayvanların beslenmesinde oldukça önemli bir yem kaynağı olabilmektedir. Bunun yanında köklerindeki nodüllerle ortak yaşama girebilen, bir rhizobium türü olan "*Rhizobium leguminosarum*" ile beraber havanın serbest azotunu toprağa fiksleyebilen ve yetiştirildiği toprağın azot miktarını artırabilen bir yapıya sahiptir (Aydoğan ve ark., 2008).

Dünyada yemeklik tane baklagiller içinde 2023 yılı itibariyle ekim alanı bakımından %7.5, üretim bakımından ise %7.95 oranı ile kuru fasulye, nohut, börülce ve bezelyeden sonra beşinci sırada yer alan mercimeğin verim değerleri bakımından ise diğer yemeklik tane baklagillerle kıyaslandığında bakla ve bezelyeden sonra üçüncü sırada kendine yer bulmuştur (FAO, 2023). Mercimek dünya üzerinde ılıman veya yarı tropik bölgelere yayılmış kuraga dayanıklı bir yemeklik tane baklagil bitkisidir. Kuru tane olarak tüketilen mercimek, en çok Orta Doğu ülkeleri ile Batı-Orta-Güney Asya ülkelerinde üretilmektedir. FAO 2023 verilerine göre mercimeğin istatistik verileri incelendiğinde dünyada mercimek üreten kıtaların başında Asya (2.994.358 ton), ülkelerin başında ise Hindistan (1.620.000 ton) gelmektedir. Kıtalar arasında verim bakımından ilk sırayı Amerika Kıtası (1.375,2 kg/ha) almaktadır. FAO (2023) verilerine göre 50 ülkede mercimek yetiştiriciliği yapılmakta olup kıtalar bazında değerlendirildiğinde Avrupa ve Asya kıtalarında 16 ülkede, Afrika kıtasında 10 ve Amerika kıtasında 8 ülkede mercimek yetiştiriciliği uzun yıllardır gerçekleştirilmektedir. Kıtalar bazında mercimek ekim alanları değerlendirildiğinde Asya kıtası 3.476.081 ha ile ilk sırada gelirken Asya kıtasının ilk sırada bulunmasında yine bir Asya ülkesi olan Hindistan büyük önem taşımaktadır ki Hindistan dünya mercimek ekim alanı bakımından ilk sırada gelmektedir.

Ülkemizde yetiştiriciliği yapılan yemeklik tane baklagillerde gerek ekim alanı gerekse üretim miktarında önemli düşüşler görülmekle birlikte 1989 yılında yemeklik tane baklagil ekim alanları toplamı 2 milyon hektarın üstündeyken 30 yıl içinde yaklaşık 883.482 hektara kadar azalma göstermiştir. Aynı şekilde 2.115.000 ton olan üretim miktarı da 1.220.244 ton seviyelerine kadar gerilemiştir. Bu durum mercimek ekiliş ve üretimine de yansımış olup 997.000 ha olan mercimek ekim alanı çok ciddi bir şekilde azalma eğimiyle 277.228 hektara, 1.040.000 ton üretim miktarı ise 353.000 ton seviyelerine kadar düşme eğilimi göstermiştir. Bun karşın yeşil mercimek ekim alanımız ise yaklaşık 39.000 ha, üretimimiz ise 43.000 ton seviyelerindedir. Yeşil mercimek ekim alanları ülkemizde Yozgat, Çorum, Kırşehir, Ankara ve Konya illerini kapsayan İç Anadolu Bölgesinde daha çok görülmektedir. Yeşil mercimeğin toplam mercimek üretim miktarı içerisinde aldığı pay yüzdesi yaklaşık olarak %7-8 arasında değişmektedir (TUİK, 2023).

Genotipik yapı ile çevre, en önemli verim unsuru olan tane veriminin ortaya konulmasında iki önemli faktör olup en uygun yetiştirme tekniklerinin belirlenmesi ile verim kabiliyeti yüksek genotiplerin değişilebilir ekolojik şartlarda yetiştiriciliğinin yapılması kaliteli yüksek ürün elde edebilmek için önemlidir. Mercimek yetiştiriciliğinin yapıldığı herhangi bir lokasyonda yüksek düzeyde verim elde edebilmek için ilk sırada bölgeye uygun genotiplerin/çeşitlerin yetiştirildiği bölge için seçimi şarttır ve çeşitlerin morfolojik/fizyolojik özelliklerin önceden belirlenmesi, belli çevre koşullarında genotipler içinden üstün verimli olanları seçmede temel oluşturmaktadır. Mercimek yetiştiriciliğinde iklim ve toprak istekleri dikkate alındığında ülkemizin büyük bir imkana sahip olduğu görülmektedir (Bozdemir, 2007).

Günümüzde artık diğer tarla bitkileri türlerinde olduğu gibi baklagil bitkisi olan mercimekte de tane verimini içine alan tarımsal özellikleri üzerinde durulması ve belli ekolojik koşullarında belli genotiplerin/çeşitlerin yüksek ekonomik dane verimi sağlayacak yetiştirme yöntemlerinin saptanması artan öneme sahip olarak görülmektedir.

Bazı yeşil mercimek genotiplerinin Sivas ekolojik koşullarında tarımsal özelliklerinin performanslarının ortaya konulması bu çalışmanın amacını oluşturmaktadır.

2. MATERYAL ve METOT

2.1. Materyal

Yürütülen çalışma, Sivas Bilim ve Teknoloji Üniversitesi'nin Tarımsal AR-GE Merkezinde yer alan deneme arazisinde 2024 yılı mercimek yetiştiriciliği döneminde gerçekleştirilmiştir. Araştırmanın yürütüldüğü lokasyon deniz seviyesinden yaklaşık 1285 m yükseklikte, N39,720656 - E36,917248 konumunda bulunmaktadır (Şekil 1).



Şekil 1. Araştırmanın yürütüldüğü deneme arazisi

Araştırmada, ülkemizde Tarımsal Araştırmalar ve Politikalar Genel Müdürlüğüne bağlı Tarımsal Araştırma Enstitüleri tarafından tescil ettirilmiş olan 3 adet yeşil mercimek çeşidi ile 2013-2016 yılları arasında BAP projesi kapsamında Kırşehir ilçe ve köylerinden toplanarak ileri düzeye kadar getirilmiş olan 27 adet yeşil mercimek hattı olmak üzere toplam 30 adet yeşil mercimek genotipi kullanılmıştır (Tablo 1 ve 2).

Tablo 1. Çalışmada kullanılan genotipler

Genotip No	İli	İlçesi	Köy/Beldesi	Genotip No	İli	İlçesi	Köy/Beldesi
M-01	**KIRŞEHİR**	Kaman	Yelek	**M-15**	**KIRŞEHİR**	Çiçekdağı	Küçükteflek
M-02		Mucur	Rışvan	**M-16**		Kaman	Tatık
M-03		Mucur	Aydoğmuş	**M-17**		Kaman	Kargıyenice
M-04		Mucur	Avcı	**M-18**		Kaman	Tatık
M-05		Mucur	Yazıkınık	**M-19**		Kaman	Ömerhacılı
M-06		Mucur	Budak	**M-20**		Boztepe	Çiğdeli
M-07		Mucur	Göynücek	**M-21**		Akçakent	Avanoğlu
M-08		Mucur	Budak	**M-22**		Akçakent	Yaylaözü
M-09		Mucur	Uşaklı	**M-23**		Akçakent	Yaylaözü
M-10		Merkez	Yeşilli	**M-26**		Akçakent	Polatlı
M-11		Mucur	Kurugöl	**M-27**		Akçakent	Polatlı
M-12		Mucur	Göynücek	**M-30**		Merkez	Sıddıklı
M-13		Mucur	Şatıroğlu	**M-31**		Kaman	Hamit
M-14		Çiçekdağı	Büyükteflek				

Tablo 2. Çalışmada kullanılan çeşitler ile tescil ettiren kuruluşlar

Mercimek Çeşitleri	Tescil Ettiren Kuruluş
Sultan	Geçit Kuşağı Tarımsal Araştırma Enstitüsü Müdürlüğü / Eskişehir
Ankara Yeşili	Tarla Bitkileri Merkez Araştırma Enstitüsü Müdürlüğü / Ankara
Meyveci 2001	

2.2. Araştırma Yerinin İklim Özellikleri

Sivas ilinin mercimek yetiştirme dönemine ait uzun yıllar ortalaması (1980-2023) ile araştırmanın yürütüldüğü 2024 yılının meteorolojik değerleri incelendiğinde uzun yıllar ortalaması ile 2024 yılına ait aylık sıcaklık ortalamaları ve aylık toplam yağış değerleri arasında Nisan ayı hariç büyük bir farkın olmadığı belirlenmiştir. Bununla birlikte 2024 yılı aylık ortalama nisbi nem değerlerinin de uzun yıllar ortalamasıyla paralellik gösterdiği Tablo 2'de ortaya konulmuştur.

Tablo 3 Sivas ilinin 2024 yılı ile uzun yıllara ait iklim verileri

Aylar	Ortalama Sıcaklık (^{0}C)		Toplam Yağış (mm)		Ortalama Nisbi Nem (%)	
	2024	**Uzun Yıllar**	**2024**	**Uzun Yıllar**	**2024**	**Uzun Yıllar**
Nisan	13.9	8.9	11.2	56.9	52.85	44.8
Mayıs	13.1	13.5	60.0	60.9	63.71	61.5
Haziran	20.9	17.0	11.6	34.5	59.45	58.0
Temmuz	22.0	20.0	37.0	9.2	53.25	49.1
Ağustos	22.0	20.2	10.2	6.8	47.43	45.9
Toplam	-	-	130.0	168.3	-	-

2.3. Toprak Özellikleri

Çalışmanın yürütüldüğü deneme arazisinin toprak öğeleri incelendiğinde deneme parselinin toprağının alkali seviyesinin hafif (7.28), organik madde içeriğinin orta (%1.7), alınabilir fosfor

(3.40) ve potasyum düzeyleri (93.59) bakımından orta, tuz seviyesinin tuzlu (%0.33) ve kireç içeriğinin ise kireçli (19.6) olduğu ortaya konulmuştur (Tablo 3).

Tablo 4. Deneme yeri toprağının fiziksel ve kimyasal özellikleri

Derinlik	**0-30 cm**
pH	7.28
Toplam Tuz (%)	0.33
Kireç (% CaCO3)	19.6
Organik Madde (%)	1.7
Fosfor (P2O5 kg/da)	3.40
Potasyum (K2O)	93.59

2.4. Yöntem

Yürütülen çalışma, Tesadüf Blokları Deneme Deseninde 4 tekerrürlü olacak şekilde kurulmuş olup parseller 5.0 m x 1.2 m= 6 m^2 olacak şekilde ayarlanmıştır. Mercimek genotiplerinin parsellere dağılımı tesadüfî olarak gerçekleştirilmiştir. Denemenin ekimleri 25 Nisan 2024 tarihinde tavlı toprağa gerçekleştirilmiştir. Ekimler 30 cm sıra aralığında 2-3 cm sıra üzerinde, her bir sıraya 150-200 adet tohum düşecek şekilde markörle açılan sıralara 3 cm derinliğe elle yapılmıştır. Her parsel 4 sıradan oluşmuştur. Yabancı otlarla mücadele etmek üzere ekimlerle beraber ekim sonrası ve çıkış öncesi yabancı ot ilacı uygulanmış ve tüm vejetasyon süresince 2 sefer çapa yapılmıştır. Her parsele eşit olarak dekara 15 kg DAP (2,7 kg N/da ve 6,9 kg P2O5/da) gübresi ekimle birlikte toprağa verilmiştir. Araştırmanın yürütüldüğü deneme alanındaki çeşitlerin hasadı, hasat olgunluğuna ulaştıkları dönem aralığı olan 25 Temmuz-10 Ağustos 2024 tarihleri arasında el ile yapılmıştır. Parseli oluşturan 4 sıradan her iki yandaki birer sıra ve sıra başlarından 50 cm'nin içerisinde bulunan bitkiler kenar tesiri olarak gözlem dışı bırakılarak bütün işlemler 4 m x 0.6 m = 2.4 m^2'lik alanlar üzerinden yapılmıştır. Her bir parselden hasat edilen bitkiler ayrı ayrı çuvallara konulup etiketlenerek hasat-harman sonrası gerekli ölçümler ve analizler yapılmak üzere Sivas Bilim ve Teknoloji Üniversitesi Tarım Bilimleri ve Teknoloji Fakültesi Tarla Bitkileri Bölümü'nün harman laboratuvarına getirilmiştir. Her parselden rastgele seçilen 10'ar bitkide bitki boyu, ilk bakla yüksekliği, biyolojik verim, bitkide bakla sayısı, bitkide tane sayısı, bin tane ağırlığı, bitkide tane verimi ve hasat indeksi değerleri saptanmış ve bunların ortalamaları alınarak bitki başına ortalama değerler hesaplanmıştır.

2.5. Verilerin Değerlendirilmesi

Çalışmadan elde edilen veriler varyans analizine tabi tutulmuş olup özelliklere ait eldeki veriler arasındaki farklılığın istatistiksel kontrolünde JUMP.13 istatistiki paket programı uygulanmıştır. Önemli çıkanlar arasındaki farklılığın hangi ya da hangilerinden kaynaklandığını belirlemek için ise LSD testi ($P>0.05$) uygulanmıştır.

3. ELDE EDİLEN BULGULAR ve TARTIŞMA

3.1. Bitki Boyu

Yürütülen çalışmada yeşil mercimek genotiplerinde tespit edilen bitki boyuna ilişkin değerler Tablo 4'de verilmiştir. Bitki boyu bakımından elde edilen veriler incelendiğinde yeşil mercimek genotipleri arasında önemli derecede ($p<0.05$) istatistiki farklılığın olduğu görülmüş

olup genotiplerin bitki boyu değerlerinin 17.00-30.00 cm arasında değişim gösterdiği belirlenmiştir. Çalışmada en yüksek bitki boyu 30.00 cm ile M-07 nolu genotipte ortaya konulurken en düşük bitki boyu değeri ise 17.00 cm değeri ile M-10 nolu genotipte saptanmış olup yeşil mercimek genotiplerinin ortalama bitki boyu değerinin ise 22.18 cm olarak ölçüldüğü tespit edilmiştir.

Tablo 5. Denemede yer alan mercimek genotiplerine ait bitki boyu (cm) değerleri ve istatistiki gruplandırmaları

Sıra No	Genotip/ Çeşitler	BB	Sıra No	Genotip/ Çeşitler	BB	Sıra No	Genotip/ Çeşitler	BB
1	M-14	22.70 ef	11	M-22	23.00 e	21	M-13	24.50 de
2	M-05	27.00 b	12	M-20	26.00 c	22	M-06	25.00 d
3	Sultan	22.00 f	13	Meyveci 2001	20.50 g	23	M-17	19.00 ı
4	M-15	23.00 e	14	M-18	22.50 efg	24	M-01	19.50 hı
5	M-27	24.50 de	15	M-03	22.00 f	**25**	**M-10**	**17.00 l**
6	M-31	19.50 hı	16	M-30	19.70 h	26	M-26	21.50 fg
7	Ankara Yeşili	19.00 ı	17	M-16	17.60 k	27	M-19	23.00 e
8	M-02	27.00 b	**18**	**M-07**	**30.00 a**	28	M-21	18.00 jk
9	M-12	21.50 fg	19	M-09	23.00 e	29	M-08	18.40 j
10	M-23	23.00 e	20	M-04	23.00 e	30	M-11	23.00 e
Minimum - Maximum		17.00-30.00						
Ortalama		22.18						
Önemlilik		*						
CV (%)		8.67						

Güneydoğu Anadolu Bölgesi'nde verim potansiyeli yüksek çeşitlerin belirlenebilmesi için 1995-1997 yılları arasında 2 yıl süreyle 25 kırmızı mercimek çeşidinin materyal olarak kullanıldığı çalışmanın iki yıllık sonuçlarına göre bitki boyunun 30.00-38.70 cm arasında değişim gösterdiği Türk ve ark. (1999) tarafından rapor edilmiş olup bu agronomik özellik üzerine yürütülen diğer çalışmalarda Gupta ve ark. (1996) Hindistan ekolojik koşullarında 6.20-24.20 cm, Kaçar ve Azkan (1997) Bursa ekolojik koşullarında 19.90-27.90 cm, Türk ve Atikyılmaz (2000) Diyarbakır ekolojik koşullarında 34.80-58.80 cm, Bildirici ve Çiftçi (2001) Van ekolojik koşullarında 22.20-25.80 cm, Erman ve ark. (2005) Siirt ekolojik koşullarında 31.80-48.50 cm, Demirhan (2006) Siirt ekolojik koşullarında 31.80-48.50 cm, Bozdemir (2007) Ankara ekolojik koşullarında 28.90-38.00 cm, Bozdemir ve Önder (2009) Ankara ekolojik koşullarında 28.90-38.00 cm, Ölmez (2011) Adıyaman ekolojik koşullarında 41.00-48.70 cm, Canbolat (2014) Kahramanmaraş ekolojik koşullarında 44.48-45.55 cm, Öktem (2016) Şanlıurfa ekolojik koşullarında 37.30-45.10 cm, Alabay (2019) Konya ekolojik koşullarında 25.03-29.83 cm ve Küçükay ve ark. (2019) Isparta ekolojik koşullarında 27.50-32.80 cm değerlerini elde etmişlerdir.

3.2. İlk Bakla Yüksekliği

Yürütülen çalışmada yeşil mercimek genotiplerinde tespit edilen ilk bakla yüksekliğine ilişkin değerler Tablo 5'de verilmiştir. İlk bakla yüksekliği bakımından elde edilen veriler

incelendiğinde yeşil mercimek genotipleri arasında önemli derecede ($p<0.05$) istatistiki farklılığın olduğu görülmüş olup yeşil mercimek genotiplerinin bitki boyu değerlerinin 9.50-22.00 cm arasında değişim gösterdiği belirlenmiştir. Tablo, ilk bakla yüksekliği değerleri bakımından değerlendirildiğinde en yüksek ilk bakla yüksekliği 22.00 cm değeri ile Sultan çeşidinde tespit edilirken en düşük ilk bakla yüksekliği ise 9.50 cm değeri ile M-16 nolu genotipinde belirlenmiş olup tüm yeşil mercimek genotiplerinin ise ortalama ilk bakla yüksekliği değerinin 14.26 cm olarak ölçüldüğü ortaya konulmuştur.

Tablo 6. Denemede yer alan mercimek genotiplerine ait ilk bakla yüksekliği (cm) değerleri ve istatistiki gruplandırmaları

Sıra No	Genotip/ Çeşitler	İBY	Sıra No	Genotip/ Çeşitler	İBY	Sıra No	Genotip/ Çeşitler	İBY
1	M-14	11.80 gh	11	M-22	16.00 c	21	M-13	12.60 fg
2	M-05	17.50 b	12	M-20	15.00 d	22	M-06	16.00 c
3	**Sultan**	**22.00 a**	13	Meyveci 2001	13.00 f	23	M-17	15.00 d
4	M-15	14.00 ef	14	M-18	12.00 g	24	M-01	10.30 ı
5	M-27	14.30 e	15	M-03	17.50 b	25	M-10	11.00 h
6	M-31	10.00 ıj	16	M-30	10.10 ıj	26	M-26	10.00 ıj
7	Ankara Yeşili	15.00 d	**17**	**M-16**	**9.50 j**	27	M-19	14.00 ef
8	M-02	17.00 bc	18	M-07	17.00 bc	28	M-21	12.60 fg
9	M-12	13.00 f	19	M-09	17.00 bc	29	M-08	14.50 de
10	M-23	17.00 bc	20	M-04	16.00 c	30	M-11	17.00 bc
Minimum - Maximum		9.50-22.00						
Ortalama		14.26						
Önemlilik		*						
CV (%)		7.91						

Kuru tarımın yoğun bir şekilde yapıldığı Ankara ekolojik koşullarında 2001-2003 yılları arasında 2 yıl süreyle farklı toprak işleme ve yabancı ot kontrolü yöntemlerinin mercimekte verim ve yabancı ot yoğunluğunun belirlenmesi için yürütülen çalışmada ilk bakla yükseklik değerinin 15.00-22.00 cm arasında değişim gösterdiği Kayan ve Adak (2006) tarafından rapor edilmiş olup bu agronomik özellik üzerine yürütülen diğer çalışmalarda Stoilova ve Pereira (1998) Bulgaristan ekolojik koşullarında 7.00-25.80 cm, Türk ve Atikyılmaz (2000) Diyarbakır ekolojik koşullarında 14.00-30.00 cm, Toğay (2002) Van ekolojik koşullarında 12.18-14.76 cm, Erman ve ark. (2005) Siirt ekolojik koşullarında 10.00-16.00 cm, Demirhan (2006) Siirt ekolojik koşullarında 10.00-16.00 cm, Bozdemir (2007) Ankara ekolojik koşullarında 14.40-20.10 cm, Biçer ve Şakar (2008a) Diyarbakır ekolojik koşullarında 13.50 cm, Ölmez (2011) Adıyaman ekolojik koşullarında 3.65-5.42 cm, Kayan ve Olgun (2012) Eskişehir ekolojik koşullarında 18.07 cm, Canbolat (2014) Kahramanmaraş ekolojik koşullarında 25.31-25.84 cm, Güneş (2016) Kahramanmaraş ekolojik koşullarında 19.40-19.50 cm, Alabay (2019) Konya ekolojik koşullarında 11.33-12.16 cm, Küçükay ve ark. (2019) Isparta ekolojik koşullarında 9.23-20.20 cm ve Tekin (2019) Batman ekolojik koşullarında 12.27-18.90 cm değerlerini sağlamışlardır.

3.3. Biyolojik Verim

Yürütülen çalışmada biyolojik verim bakımından yeşil mercimek genotipleri arasındaki farklılık istatistiki yönden çok önemli ($p<0.01$) bulunmuştur. Yeşil mercimek genotiplerinde biyolojik verime ilişkin ortalama değerler Tablo 6'da verilmiştir. Biyolojik verim değerleri bakımından tablo incelendiğinde en yüksek biyolojik verim, 11.10 g değeri ile M-15 nolu genotipinde tespit edilirken en düşük biyolojik verim değeri ise 3.28 g değeri ile Meyveci 2001

çeşidinde saptanmış olup tüm yeşil mercimek genotiplerinin ise ortalama biyolojik verim değerinin 5.98 g olarak tespit edildiği ortaya konulmuştur.

Tablo 7. Denemede yer alan mercimek genotiplerine ait biyolojik verim (g) değerleri ve istatistiki gruplandırmaları

Sıra No	Genotip/ Çeşitler	BV	Sıra No	Genotip/ Çeşitler	BV	Sıra No	Genotip/ Çeşitler	BV
1	M-14	9.78 b	11	M-22	7.27 de	21	M-13	4.85 hı
2	M-05	5.60 g	12	M-20	5.17 ghı	22	M-06	4.82 hı
3	Sultan	6.81 e	**13**	**Meyveci 2001**	**3.28 l**	23	M-17	5.81 fgh
4	**M-15**	**11.10 a**	14	M-18	7.76 d	24	M-01	3.64 k
5	M-27	6.21 f	15	M-03	5.21 ghı	25	M-10	5.09 h
6	M-31	5.90 fg	16	M-30	5.59 g	26	M-26	3.99 jk
7	Ankara Yeşili	5.88 fg	17	M-16	5.54 gh	27	M-19	8.14 c
8	M-02	8.48 bc	18	M-07	6.40 ef	28	M-21	4.63 ı
9	M-12	5.61 g	19	M-09	5.50 gh	29	M-08	4.19 j
10	M-23	8.05 cd	20	M-04	5.09 h	30	M-11	3.97 jk
Minimum - Maximum		3.28-11.10						
Ortalama		5.98						
Önemlilik		**						
CV (%)		10.17						

Her parselden rastgele seçilen 10'ar adet bitkinin 0.01 g duyarlı terazide ayrı ayrı tartılması ve ortalamasının alınmasıyla hesaplanan bitki başına biyolojik verim değeri, verim unsurları içinde önemli agronomik özelliklerden bir tanesidir. Gerek bitki başına tane verimini gerekse dekara tane verimini arttırmada en önemli üç verim unsurunun biyolojik verim, hasat indeksi ve vejetasyon süresi olduğu Wallace ve ark. (1993) tarafından ifade edilmekle birlikte aynı zamanda tarla bitkisi türlerinde dekara tane verim ile bitkide tane verim üzerine yapılacak seleksiyonlarda bu üç özellik arasındaki ilişkiyi çok iyi bilmek gerektiği belirtilmekte olup bu agronomik özellik üzerine yürütülen diğer araştırmalarda Şakar ve ark. (1997) Diyarbakır ekolojik koşullarında 3.00-9.40 g, Karadavut ve ark. (1999) Amik Ovası ekolojik koşullarında 2.69-4.33 g, Biçer ve ark. (2001) Diyarbakır ekolojik koşullarında 1.525-4.932 g, Bucak ve ark. (2003) Harran Ovası ekolojik koşullarında 3.36-4.64 g, Erman ve ark. (2005) Siirt ekolojik koşullarında 5.93-7.68 g, Kayan ve Adak (2006) Ankara ekolojik koşullarında 3.14-5.50 g, Biçer ve Şakar (2008a) Diyarbakır ekolojik koşullarında 2.93 g, Tyagi ve Khan (2011) Hindistan ekolojik koşullarında 6.40-6.50 g, Kayan ve Olgun (2012) Eskişehir ekolojik koşullarında 4.48 g, Canbolat (2014) Kahramanmaraş ekolojik koşullarında 3.41-3.82 g ve Alabay (2019) Konya ekolojik koşullarında 3.56 g arasında değerleri elde etmişlerdir.

3.4. Bitkide Bakla Sayısı

Çalışmada yer alan yeşil mercimek genotiplerinin bitkide bakla sayısı üzerine etkisinin çok önemli ($p<0.01$) olduğu araştırmada en yüksek bitkide bakla sayısı 51.00 adet ile M-22 nolu genotipten elde edilirken M-08 nolu genotipi ise yeşil mercimek genotipleri içinde 19.00 adet bitkide bakla sayısı değeri ile son sırada yer almış olup yeşil mercimek genotiplerinin ortalama bitkide bakla sayısı değerinin ise 31.73 adet olarak elde edildiği görülmüştür.

Tablo 8. Denemede yer alan mercimek genotiplerine ait bitkide bakla sayısı (adet) değerleri ve istatistiki gruplandırmaları

Sıra No	Genotip/ Çeşitler	BBS	Sıra No	Genotip/ Çeşitler	BBS	Sıra No	Genotip/ Çeşitler	BBS
1	M-14	21.00 j	**11**	**M-22**	**51.00 a**	21	M-13	24.00 ıj
2	M-05	39.00 cd	12	M-20	35.00 e	22	M-06	33.00 f
3	Sultan	31.00 g	13	Meyveci 2001	37.00 d	23	M-17	37.00 d
4	M-15	45.00 b	14	M-18	31.00 g	24	M-01	25.00 ı
5	M-27	19.00 k	15	M-03	29.00 h	25	M-10	20.00 jk
6	M-31	39.00 cd	16	M-30	25.00 ı	26	M-26	36.00 de
7	Ankara Yeşili	40.00 c	17	M-16	20.00 jk	27	M-19	28.00 hı
8	M-02	33.00 f	18	M-07	28.00 hı	28	M-21	35.00 e
9	M-12	35.00 e	19	M-09	33.00 f	**29**	**M-08**	**19.00 k**
10	M-23	33.00 f	20	M-04	36.00 de	30	M-11	35.00 e
Minimum - Maximum		19.00-51.00						
Ortalama		31.73						
Önemlilik		**						
CV (%)		13.69						

Bulgaristan ekolojik koşullarında 120 adet mercimek genotipinin iki yıl süreyle verim ve verim öğelerinin belirlenmesi üzerine yürütülen çalışmada denemeye alınan mercimek genotipleri arasında incelenen tüm özelliklerde genetik yapıdan kaynaklanan varyasyonlar olduğu Stoilova ve Pereira (1998) tarafından belirtmiş olmakla birlikte yürütülen araştırmada materyallerin bitkide bakla sayısı değerinin 9.80-65.70 adet arasında değişim gösterdiği rapor edilmiş olup bu agronomik özellik üzerine yürütülen diğer araştırmalarda Karadavut ve ark. (1999) Amik Ovası ekolojik koşullarında 20.16-33.90 adet, Türk ve Atikyılmaz (2000) Diyarbakır ekolojik koşullarında 6.20-59.30 adet, Biçer ve ark. (2001) Diyarbakır ekolojik koşullarında 12.10-43.80 adet, Erman ve ark. (2005) Siirt ekolojik koşullarında 9.50-34.50 adet, Demirhan (2006) Siirt ekolojik koşullarında 9.50-34.50 adet, Biçer ve Şakar (2007) Diyarbakır ekolojik koşullarında 22.50-41.10 adet, Bozdemir (2007) Ankara ekolojik koşullarında 10.30-15.10 adet, Güneş (2016) Kahramanmaraş ekolojik koşullarında 41.00-49.22 adet, Mekonnen ve ark. (2014) Etiopya ekolojik koşullarında 27.80-43.30 adet, Toklu ve ark. (2017) Adana ve Sivas illeri ekolojik koşullarında sırasıyla 12.00-74.30 adet ile 10.80-113.60 adet, Küçükay ve ark. (2019) Isparta ekolojik koşullarında 30.13-50.73 adet ve Tekin (2019) Batman ekolojik koşullarında 12.07-28.07 adet arasında değerler elde etmişlerdir.

3.5. Bitkide Tane Sayısı

Yeşil mercimek genotipleri arasında bitkide tane sayısı bakımından çok önemli ($p<0.01$) farklılığın bulunduğu çalışmada en yüksek bitkide tane sayısı 55.00 adet ile M-11 nolu genotipinde ortaya konulurken M-16 nolu genotipi ise tüm yeşil mercimek genotipleri içinde 14.00 adet bitkide tane sayısı değeri ile son sırada yer almış olup tüm yeşil mercimek genotiplerinin ortalama bitkide tane sayısı değerinin ise 32.13 adet olarak saptandığı görülmüştür.

Tablo 9. Denemede yer alan mercimek genotiplerine ait bitkide tane sayısı (adet) değerleri ve istatistiki gruplandırmaları

Sıra No	Genotip/ Çeşitler	BBS	Sıra No	Genotip/ Çeşitler	BBS	Sıra No	Genotip/ Çeşitler	BBS
1	M-14	16.00 l	11	M-22	27.00 ı	21	M-13	21.00 k
2	M-05	31.00 h	12	M-20	33.00 g	22	M-06	50.00 b
3	Sultan	31.00 h	13	Meyveci 2001	35.00 fg	23	M-17	32.00 gh
4	M-15	48.00 c	14	M-18	32.00 gh	24	M-01	26.00 ıj
5	M-27	33.00 g	15	M-03	30.00 hı	25	M-10	24.00 j
6	M-31	42.00 d	16	M-30	21.00 k	26	M-26	47.00 cd
7	Ankara Yeşili	36.00 f	**17**	**M-16**	**14.00 m**	27	M-19	20.00 kl
8	M-02	30.00 hı	18	M-07	39.00 e	28	M-21	26.00 ıj
9	M-12	36.00 f	19	M-09	35.00 fg	29	M-08	20.00 kl
10	M-23	32.00 gh	20	M-04	42.00 d	**30**	**M-11**	**55.00 a**
Minimum - Maximum		14.00-55.00						
Ortalama		32.13						
Önemlilik		**						
CV (%)		14.19						

Tıpkı bitkide bakla sayısı özelliğinde olduğu gibi bitkide tane sayısı da gerek bitkide tane verimi gerekse dekara tane verimi ile önemli/çok önemli ve pozitif/olumlu ilişkiler göstermekle birlikte ıslah çalışmalarında genotip ve çeşitlerin bir üst generasyona aktarılmasında dikkate alınması gereken önemli bir agronomik özelliktir. Nitekim mercimek bitkisinde bitkide bakla sayısı ile tane sayısının genetik yapıdan, ekim sıklığından ve yetiştirme tekniğinden uygulanan işlemlere göre değişim gösterebildiği bitkide tane sayısının dekara tane verimini belirleyen en önemli verim öğeleri arasında olabileceği Adak (2021) tarafından rapor edilmiş olup bu agronomik özellik üzerine yürütülen diğer çalışmalarda Kaçar ve Azkan (1997) Bursa ekolojik koşullarında 10.4-16.5 adet, Stoilova ve Pereira (1998) Bulgaristan ekolojik koşullarında 9.7-75.5 adet, Şakar ve Biçer (2001) Diyarbakır ekolojik koşullarında 115.4-118.6 adet, Koç (2004) Diyarbakır ekolojik koşullarında 23.9-57.4 adet, Erman ve ark. (2005) Siirt ekolojik koşullarında 12.8-54.3 adet, Demirhan (2006) Siirt ekolojik koşullarında 12.8-54.3 adet, Kayan ve Adak (2006) Ankara ekolojik koşullarında 23-38 adet, Biçer ve Şakar (2007) Diyarbakır ekolojik koşullarında 33.1-57.9, Çokkızgın (2007) Kahramanmaraş ekolojik koşullarında 26.8-50.6 adet, Sözen ve Karadavut (2017) Kırşehir ekolojik koşullarında 10.7-18.5 adet, Alabay (2019) Konya ekolojik koşullarında 20.4-24.13 adet, Küçükay ve ark. (2019) Isparta ekolojik koşullarında 40.96-64.7 adet ve Tekin (2019) Batman ekolojik koşullarında 20.12-47.28 adet arasında kalan değerler elde etmişlerdir.

3.6. 1000 Tane Ağırlığı

Yeşil mercimek genotiplerinin bin tane ağırlık üzerine etkisinin çok önemli ($p<0.01$) bulunduğu çalışmada değişim aralığının 33.47-49.75 g olarak oluştuğu görülmüş olup en yüksek bin tane ağırlığı 49.75 g ile M-04 nolu genotipinden, en düşük bin tane ağırlığı ise 33.47 g ile M-11 nolu genotipte ortaya konulurken tüm yeşil mercimek genotiplerinin ortalama bin tane ağırlığı değerinin 42.71 g olarak belirlendiği görülmüştür. İran'da 16 mercimek çeşidinin 2008-2010 yılları arasında 2 yıl süre ile verim ve verim öğelerinin belirlenmesi üzerine yürütülen çalışmada ortalama bin tane ağırlığının 42.91 g olarak değer aldığı Abdipur ve ark. (2011) tarafından ifade edilmiş olup bu özellik üzerine yürütülen diğer çalışmalarda Kaçar ve Azkan (1997) Bursa ekolojik koşullarında 38.1-72.4 g, Stoilova ve Pereira (1998) Bulgaristan ekolojik koşullarında 18-68 g, Toğay (2002) Van ekolojik koşullarında 37.06-59.14 g, Bucak ve ark. (2003) Harran

ekolojik koşullarında 33.06-40.64 g, Koç (2004) Diyarbakır ekolojik koşullarında 25.25-50.50 g, Erman ve ark. (2005) Siirt ekolojik koşullarında 26.3-65.5 g, Demirhan (2006) Siirt ekolojik koşullarında 26.3-65.5 g, Bozdemir (2007) Ankara ekolojik koşullarında 54.8-74.4 g, Çokkızgın (2007) Kahramanmaraş ekolojik koşullarında 24.85-39.40 g, Biçer ve Şakar (2010) Diyarbakır ekolojik koşularında 36.27 g, Kayan ve Olgun (2012) Eskişehir ekolojik koşullarında 52.4 g, Katiyar ve Kant (2015) Hindistan ekolojik koşullarında 28.3 g, Güneş (2016) Kahramanmaraş ekolojik koşullarında 35.03-38.66 g, Öktem (2016) Şanlıurfa ekolojik koşullarında 33.55-46.1 g, Küçükay ve ark. (2019) Isparta ekolojik koşullarında 29.1-36.4 g, Tekin (2019) Batman ekolojik koşullarında 25.93-43.60 g ve Faqeer ve ark. (2020) Pakistan ekolojik koşullarında 60.09 g arasında yer alan değerlere ulaşmışlardır.

Tablo 10. Denemede yer alan mercimek genotiplerine ait bin tane ağırlığı (g) değerleri ve istatistiki gruplandırmaları

Sıra No	Genotip/ Çeşitler	BBS	Sıra No	Genotip/ Çeşitler	BBS	Sıra No	Genotip/ Çeşitler	BBS
1	M-14	44.81 g	11	M-22	40.77 mn	21	M-13	49.16 b
2	M-05	43.56 ı	12	M-20	42.73 j	22	M-06	40.55 mno
3	Sultan	41.27 l	13	Meyveci 2001	48.28 d	23	M-17	42.18 jkl
4	M-15	38.95 n	14	M-18	44.35 h	24	M-01	45.54 f
5	M-27	44.21 hı	15	M-03	48.81 c	25	M-10	40.88 m
6	M-31	43.17 ıjk	16	M-30	48.55 cd	26	M-26	41.07 lmn
7	Ankara Yeşili	43.36 ıj	17	M-16	42.18 jkl	27	M-19	45.52 f
8	M-02	37.82 o	18	M-07	34.74 op	28	M-21	42.63 jk
9	M-12	41.95 k	19	M-09	41.16 lm	29	M-08	33.94 p
10	M-23	46.14 e	**20**	**M-04**	**49.75 a**	**30**	**M-11**	**33.47 pq**
Minimum - Maximum		33.47-49.75						
Ortalama		42.71						
Önemlilik		**						
CV (%)		3.52						

3.7. Bitkide Tane Verimi

Yürütülen çalışma sonucunda yeşil mercimek genotiplerinden elde edilen bitkide tane verimine ait değerlerin 1.84-3.51 g arasında değişim gösterdiği belirlenmiş olup yeşil mercimek genotiplerinin bitkide tane verim değerleri arasındaki farklılığın istatistiksel olarak önemli ($p<0.05$) olduğu görülmüştür. M-14 nolu genotip, bitkide tane verimi bakımından en yüksek değere (3.51 g) sahip olurken en düşük bitkide tane verim değeri ise 1.84 g ile M-11 nolu genotipte belirlenmiş olup tüm yeşil mercimek genotiplerinin ortalama bitki başına tane verim değerinin ise 2.34 g olduğu ortaya konulmuştur. Diyarbakır ilinde mercimek genotiplerinin verim ve verim öğelerinin belirlenmesi üzerine 1996 yılında yürütülen araştırmada genotiplerin bitkide tane verimi değerlerinin 0.512-2.070 g arasında değişim gösterdiği Biçer ve ark. (2001) tarafından rapor edilmiş olup bu parametre üzerine yürütülen diğer çalışmalarda ise Stoilova ve Pereira (1998) Bulgaristan ekolojik koşullarında 1.1-9.5 g, Türk ve Atikyılmaz (2000) Diyarbakır ekolojik koşullarında 22.8-46.3 g, Şakar ve Biçer (2001) Diyarbakır ekolojik koşullarında 2.32-24.88 g, Demirhan (2006) Siirt ekolojik koşullarında 0.83-1.56 g, Biçer ve Şakar (2007) Diyarbakır ekolojik koşullarında 0.7-1.8 g, Çokkızgın (2007) Kahramanmaraş ekolojik koşullarında 0.682-1.645 g, Roy ve ark. (2013) Bangladeş ekolojik koşullarında 2.13 g, Hussain ve ark. (2014) Pakistan ekolojik koşullarında 13.8-27.9 g ve Küçükay ve ark. (2019) Isparta ekolojik koşullarında 0.49-2.07 g aralığında yer alan değerleri elde etmişlerdir.

Tablo 11. Denemede yer alan mercimek genotiplerine ait bitkide tane verimi (g) değerleri ve istatistiki gruplandırmaları

Sıra No	Genotip/ Çeşitler	BTV	Sıra No	Genotip/ Çeşitler	BTV	Sıra No	Genotip/ Çeşitler	BTV
1	**M-14**	**3,51 a**	11	M-22	2,45 e	21	M-13	2,08 hı
2	M-05	2,90 b	12	M-20	2,40 ef	22	M-06	2,04 hıj
3	Sultan	2,83 c	13	Meyveci 2001	2,39 efg	23	M-17	1,99 ı
4	M-15	2,83 c	14	M-18	2,38 f	24	M-01	1,96 ıj
5	M-27	2,78 cd	15	M-03	2,37 fg	25	M-10	1,94 ıjk
6	M-31	2,65 d	16	M-30	2,28 g	26	M-26	1,93 ıjk
7	Ankara Yeşili	2,64 d	17	M-16	2,27 gh	27	M-19	1,91 j
8	M-02	2,61 de	18	M-07	2,20 ghı	28	M-21	1,89 jk
9	M-12	2,59 def	19	M-09	2,10 h	29	M-08	1,86 jkl
10	M-23	2,45 e	20	M-04	2,09 h	**30**	**M-11**	**1,84 k**
Minimum - Maximum		1.84-3.51						
Ortalama		2.34						
Önemlilik		*						
CV (%)		14.89						

3.8. Hasat İndeksi

Yürütülen çalışmada hasat indeksi bakımından yeşil mercimek genotipleri arasındaki farklılık istatistiki yönden çok önemli ($p<0.01$) olup yeşil mercimek genotiplerinde hasat indeksine ilişkin ortalama değerler Tablo 11'de verilmiştir. Hasat indeksi değerleri bakımından Tablo incelendiğinde en yüksek hasat indeksi %53.85 değeri ile M-01 nolu genotipinde tespit edilirken en düşük hasat indeksi değeri ise %23.46 değeri ile M-19 nolu genotipinde belirlenmiş olup tüm yeşil mercimek genotiplerinin ise ortalama hasat indeksi değerinin %40.20 olarak ölçüldüğü ortaya konulmuştur.

Tablo 12. Denemede yer alan mercimek genotiplerine ait hasat indeksi (%) değerleri ve istatistiki gruplandırmaları

Sıra No	Genotip/ Çeşitler	BBS	Sıra No	Genotip/ Çeşitler	BBS	Sıra No	Genotip/ Çeşitler	BBS
1	M-14	35.89 j	11	M-22	33.70 klm	21	M-13	42.89 g
2	M-05	51.79 b	12	M-20	46.42 d	22	M-06	42.32 gh
3	Sultan	41.56 h	13	Meyveci 2001	42.87 g	23	M-17	34.25 kl
4	M-15	25.50 m	14	M-18	30.67 lm	**24**	**M-01**	**53.85 a**
5	M-27	44.77 efg	15	M-03	45.49 e	25	M-10	38.11 ıj
6	M-31	44.92 ef	16	M-30	40.79 h-k	26	M-26	48.37 c
7	Ankara Yeşili	44.90 ef	17	M-16	40.97 hıj	**27**	**M-19**	**23.46 n**
8	M-02	30.78 l	18	M-07	34.38 k	28	M-21	40.82 h-k
9	M-12	46.17 def	19	M-09	38.18 ı	29	M-08	44.39 f
10	M-23	30.43 lmn	20	M-04	41.06 hı	30	M-11	46.35 de
Minimum - Maximum		23.46-53.85						
Ortalama		40.20						
Önemlilik		**						
CV (%)		5.96						

Amik Ovası koşullarında yetiştirilebilecek yüksek verimli mercimek hatlarının belirlenmesi amacıyla ICARDA kökenli 24 mercimek hattı ile 1996-1998 yılları arasında 2 yıl süre ile yürütülen araştırmada hasat indeksinin %17.83-30.53 aralığında değişim gösterdiği Karadavut

ve ark. (1999) tarafından rapor edilmiş olup bu özellik üzerine yürütülen diğer çalışmalarda Kaçar ve Azkan (1997) Bursa ekolojik koşullarında %18.80-33.70, Şakar ve ark. (1997) Diyarbakır ekolojik koşullarında %16.00-43.00, Biçer ve ark. (2001) Diyarbakır ekolojik koşullarında %24.00-49.00, Erman ve ark. (2005) Siirt ekolojik koşullarında %25.10-38.70, Demirhan (2006) Siirt ekolojik koşullarında %25.10-38.70, Abdipur ve ark. (2011) İran ekolojik koşullarında %31.20, Biçer ve Şakar (2011) Diyarbakır ekolojik koşullarında %30.90, Ölmez (2011) Besni/Adıyaman ekolojik koşullarında %30.00-54.00, Kayan ve Olgun (2012) Eskişehir ekolojik koşullarında %29.98, Sharma ve ark. (2013) Faizabad ekolojik koşullarında %24.11-42.13, Canbolat (2014) Kahramanmaraş ekolojik koşullarında %44.65-45.94 ve Tekin (2019) Batman ekolojik koşullarında %22.68-46.76 aralığında yer alan değerleri elde etmişlerdir.

4. SONUÇ

Bazı yeşil mercimek genotiplerinin 2024 yılında Sivas ekolojik koşullarında tarımsal özelliklerinin ortaya konulabilmesi amacıyla yürütülen araştırma sonuçlarına göre M-5, M-14, M-15 ve M-31 nolu genotiplerinin Sivas ekolojik koşulları için uygun yeşil mercimek genotip adayları oldukları ancak bu tür yürütülecek adaptasyon çalışmalarında elde edilecek verilerden daha sağlam tavsiyelerde bulunulabilmesi için ortaya konulacak çalışmaların en az 2-3 yıl daha tekrarlanmasının gerekliliği sonucuna ulaşılmıştır.

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BAZI MERCİMEK ÇEŞİTLERİNİN KALİTE ÖZELLİKLERİNİN ORTAYA KONULMASI

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ÖZET

Bazı mercimek çeşitlerine ait kalite özelliklerinin Sivas ekolojisinde belirlenmesi amacıyla 2024 yılında yürütülen çalışma, Sivas Bilim ve Teknoloji Üniversitesine ait AR-GE Tarımsal Araştırma Merkezinde yer alan deneme parsellerinde yürütülmüştür. Çalışmada 10 adet yeşil mercimek çeşidi kullanılmıştır. Bir yıl süresince yürütülen çalışma, tesadüf blokları deneme deseninde 3 tekerrürlü olarak kurulmuştur. Çalışma süresince mercimek çeşitlerine ait kalite özelliklerinin (su alma kapasitesi (g/tane), su alma indeksi (%), şişme kapasitesi (ml/tane), şişme indeksi (%), kabuk oranı (%) ve protein oranı (%)) değerleri ortaya konulmaya çalışılmıştır. Yapılan varyans analiz sonuçlarına göre ele alınan kalite özellikleri içinde tüm özellikler bakımından yeşil mercimek çeşitleri arasında istatistiksel anlamda önemli/çok önemli farklılıklar belirlenmiş olup yürütülen çalışmada en yüksek protein oranı %29.64 ile Gümrah mercimek çeşidinde görülürken en düşük protein oranı ise %23.05 ile Çiftçi mercimek çeşidinde saptanmıştır.

Anahtar Kelimeler: Sivas, Mercimek, Çeşit, Kalite, Protein

1. GİRİŞ

Mercimek, bir yemeklik tane baklagil türü olup gerek dünya gerekse ülkemizde yaşamını sürdüren insanların beslenme sürecinde önemli bir yer tutmakla birlikte bu önemi yüksek içerikli protein ve karbonhidrattan kaynaklanmaktadır. Kuru tanelerinde bulunan %18-31 oranındaki protein ile %55-70 oranındaki karbonhidrat içerikleri nedeniyle özellikle tercih edilmekte olup bunların yanında fosfor, kalsiyum ve demir gibi mineraller ile A, B1, B2 ve D vitaminlerce zenginliği insanların beslenmesine önemli katkıda bulunmaktadır (Smithson ve ark., 1985).

Mercimek, kuru tarım alanlarında bir tahıl bitkisi olan buğday veya arpa ile ekim nöbetine girebilmekle birlikte toprak verimliliğine olumlu katkısı ile yüksek gelir kazancıyla tarımsal bakımdan çok önemli bir yerde bulunmaktadır. Gerçekleştirilen hasat ile harman sonrasında tanesinden arda kalan sap/samanda çok az miktarda selüloz bulunduğu için hayvan beslenmesinde önemli bir yem kaynağı olabilmektedir. Bunun yanında köklerinde bulunan nodüllerle ortak yaşam sürdüren "*Rhizobium leguminosarum*" isimli bakteri türü ile beraber havanın serbest azotunu toprağa kazandıran ve yetiştirildiği arazinin toprağın azot miktarını artırabilen bir özelliği de bulunmaktadır (Aydoğan ve ark., 2008).

Hayvansal protein kaynakları insan beslenmesinde önem arz etmesine rağmen bu kaynakların yeterince tedarik edilemediği yerlerde bu açığı giderecek bitkisel kaynaklı proteinlere ihtiyaç duyulmaktadır. Bunun yanında hayvansal kaynaklı proteinler, protein kaynakları bakımından önem arz etmesine rağmen gerek maliyetlerinin yüksek olmaları gerek saklanmalarındaki zorluklar gerekse çabuk bozulmalarındaki riskler ile dini inanışlar gibi bazı nedenlerden ötürü kolay bir şekilde üretilip saklanabilen ve ucuza mal edilebilen bitkisel kaynaklı proteinlerin önemini bir kez daha ortaya koymaktadır.

Baklagiller (*Leguminosae*) takımının kelebek çiçekliler (*Papilionatae*) familyasına bağlı Vicieae oymağına mensup beş önemli cinsinden (*Vicia* L., *Lathyrus* L., *Pisum* L., *Cicer* L. ve *Lens* Miller) birisi olan Mercimek (Şehirali, 1988) tarımının Dünya üzerinde ılıman ve subtropik iklim bölgelerinde yapıldığı görülmekle (Lazaro ve ark., 2001) birlikte ülkemizde ise Doğu Karadeniz Bölgesi dışında kalan tüm coğrafi bölgelerde başarılı bir şekilde yetiştirilebilmektedirler.

Mercimeğin ilk kültüre alındığı yerin verimli yarım ay dediğimiz Mezopotamya ile ülkemizin Güneydoğu Anadolu Bölgesi olduğu tahmin edilmekle beraber (Özdemir, 2002) tarımının yaklaşık olarak günümüzden 8.000 yıl öncesine kadar dayandığı bilinmektedir (Pellet, 1988). Yapılan arkeolojik kazılarda Türkiye'de Hacılar, Çayönü ve Çan Hasanda M.Ö. 7000-6500, Yunanistan'da M.Ö. 6500-6000, Irak, İran ve Ürdün'de M.Ö. 7000-6500 ve Suriye'de ise M.Ö. 8500-7500 yıllarına ait mercimek fosillerinin kalıntılarına saptanmıştır (Sepetoğlu, 2002).

Dünyada yemeklik tane baklagiller içinde 2023 yılı itibariyle ekim alanı bakımından %7.5, üretim bakımından ise %7.95 oranı ile kuru fasulye, nohut, börülce ve bezelyeden sonra beşinci sırada yer alan mercimeğin verim değerleri bakımından ise diğer yemeklik tane baklagillerle kıyaslandığında bakla ve bezelyeden sonra üçüncü sırada kendine yer bulmuştur (FAO, 2023). Mercimek dünya üzerinde ılıman veya yarı tropik bölgelere yayılmış kurağa dayanıklı bir yemeklik tane baklagil bitkisidir. Kuru tane olarak tüketilen mercimek, en çok Orta Doğu ülkeleri ile Batı-Orta-Güney Asya ülkelerinde üretilmektedir. FAO 2023 verilerine göre mercimeğin istatistik verileri incelendiğinde dünyada mercimek üreten kıtaların başında Asya (2.994.358 ton), ülkelerin başında ise Hindistan (1.620.000 ton) gelmektedir. Kıtalar arasında verim bakımından ilk sırayı Amerika Kıtası (1.375,2 kg/ha) almaktadır. FAO (2023) verilerine göre 50 ülkede mercimek yetiştiriciliği yapılmakta olup kıtalar bazında değerlendirildiğinde

Avrupa ve Asya kıtalarında 16 ülkede, Afrika kıtasında 10 ve Amerika kıtasında 8 ülkede mercimek yetiştiriciliği uzun yıllardır gerçekleştirilmektedir. Kıtalar bazında mercimek ekim alanları değerlendirildiğinde Asya kıtası 3.476.081 ha ile ilk sırada gelirken Asya kıtasının ilk sırada bulunmasında yine bir Asya ülkesi olan Hindistan büyük önem taşımaktadır ki Hindistan dünya mercimek ekim alanı bakımından ilk sırada gelmektedir.

Ülkemizde yetiştiriciliği yapılan yemeklik tane baklagillerde gerek ekim alanı gerekse üretim miktarında önemli düşüşler görülmekle birlikte 1989 yılında yemeklik tane baklagil ekim alanları toplamı 2 milyon hektarın üstündeyken 30 yıl içinde yaklaşık 883.482 hektara kadar azalma göstermiştir. Aynı şekilde 2.115.000 ton olan üretim miktarı da 1.220.244 ton seviyelerine kadar gerilemiştir. Bu durum mercimek ekiliş ve üretimine de yansımış olup 997.000 ha olan mercimek ekim alanı çok ciddi bir şekilde azalma eğimiyle 277.228 hektara, 1.040.000 ton üretim miktarı ise 353.000 ton seviyelerine kadar düşme eğilimi göstermiştir. Bun karşın yeşil mercimek ekim alanımız ise yaklaşık 39.000 ha, üretimimiz ise 43.000 ton seviyelerindedir. Yeşil mercimek ekim alanları ülkemizde Yozgat, Çorum, Kırşehir, Ankara ve Konya illerini kapsayan İç Anadolu Bölgesinde daha çok görülmektedir. Yeşil mercimeğin toplam mercimek üretim miktarı içerisinde aldığı pay yüzdesi yaklaşık olarak %7-8 arasında değişmektedir (TUİK, 2023).

Tüketimdeki değişmelere bağlı olarak son yıllarda mercimek için de değişimler olabilmektedir. Islah çalışmaları kapsamında yüksek mercimek çeşitleri geliştirmekle beraber son yıllarda geliştirilecek çeşit aday/adaylarında kalite içeriklerini de artırmak amacı ön plana çıkmıştır. Yetiştiriciliğinin yapıldığı üretim sahalarında iklim ve toprak içeriklerine adapte olabilecek verimli ve kalite özellikleri amacıyla daha yüksek performans gösterebilen mercimek genotiplerinin beslenme içerikleri bakımından taşıdığı önem nedeniyle geliştirilip üretim sahalarına kazandırılması ülkemizde yaşayan insanların beslenmesi kapsamında son derece önem taşıyabilmektedir.

Yürütülen bu çalışma ile Tarımsal Araştırma Enstitüleri tarafından tescil ettirilmiş olan yeşil mercimek çeşitlerinin kalite özelliklerinin belirlenmesi amaçlanmıştır.

2. MATERYAL ve METOT

2.1. Materyal

Bu araştırmanın tarla çalışmaları Sivas Bilim ve Teknoloji Üniversitesi'nin Tarımsal AR-GE Merkezinde yer alan deneme arazisinde 2024 yılı mercimek vejetasyon döneminde yürütülmüştür. Araştırmanın yürütüldüğü lokasyon deniz seviyesinden yaklaşık 1285 m yükseklikte, N39,720656 - E36,917248 konumunda bulunmaktadır (Şekil 1).



Şekil 1. Araştırmanın yürütüldüğü deneme arazisi

Araştırmada, ülkemizde Tarımsal Araştırmalar ve Politikalar Genel Müdürlüğüne bağlı Tarımsal Araştırma Enstitüleri tarafından tescil ettirilmiş olan 10 adet yeşil mercimek çeşidi kullanılmıştır (Tablo 1).

Tablo 1. Çalışmada kullanılan çeşitler ile tescil ettiren kuruluşlar

Mercimek Çeşitleri	Tescil Ettiren Kuruluş
Sultan	Geçit Kuşağı Tarımsal Araştırma Enstitüsü Müdürlüğü / Eskişehir
Ankara Yeşili	Tarla Bitkileri Merkez Araştırma Enstitüsü Müdürlüğü / Ankara
Kafkas	
Gümrah	
Karagül	
Meyveci 2001	
Bozok	
Çiftçi	
Ceren	
Pul 11	

2.2. Araştırma Yerinin İklim Özellikleri

Sivas ilinin mercimek yetiştirme dönemine ait uzun yıllar ortalaması (1980-2023) ile araştırmanın yürütüldüğü 2024 yılının meteorolojik değerleri incelendiğinde uzun yıllar ortalaması ile 2024 yılına ait aylık sıcaklık ortalamaları ve aylık toplam yağış değerleri arasında Nisan ayı hariç büyük bir farkın olmadığı belirlenmiştir. Bununla birlikte 2024 yılı aylık ortalama nisbi nem değerlerinin de uzun yıllar ortalamasıyla paralellik gösterdiği Tablo 2'de ortaya konulmuştur.

Tablo 2. Sivas ilinin 2024 yılı ile uzun yıllara ait iklim verileri

Aylar	Ortalama Sıcaklık (^{0}C)		Toplam Yağış (mm)		Ortalama Nisbi Nem (%)	
	2024	Uzun Yıllar	2024	Uzun Yıllar	2024	Uzun Yıllar
Nisan	13.9	8.9	11.2	56.9	52.85	44.8
Mayıs	13.1	13.5	60.0	60.9	63.71	61.5
Haziran	20.9	17.0	11.6	34.5	59.45	58.0
Temmuz	22.0	20.0	37.0	9.2	53.25	49.1
Ağustos	22.0	20.2	10.2	6.8	47.43	45.9
Toplam	-	-	130.0	168.3	-	-

2.3. Toprak Özellikleri

Çalışmanın yürütüldüğü deneme arazisinin toprak öğeleri incelendiğinde deneme parselinin toprağının alkali seviyesinin hafif (7.28), organik madde içeriğinin orta (%1.7), alınabilir fosfor (3.40) ve potasyum düzeyleri (93.59) bakımından orta, tuz seviyesinin tuzlu (%0.33) ve kireç içeriğinin ise kireçli (19.6) olduğu ortaya konulmuştur (Tablo 3).

Tablo 3. Deneme yeri toprağının fiziksel ve kimyasal özellikleri

Derinlik	**0-30 cm**
pH	7.28
Toplam Tuz (%)	0.33
Kireç (% CaCO3)	19.6
Organik Madde (%)	1.7
Fosfor (P2O5 kg/da)	3.40
Potasyum (K2O)	93.59

2.4. Yöntem

Yürütülen çalışma, Tesadüf Blokları Deneme Deseninde 4 tekerrürlü olacak şekilde kurulmuş olup parseller 5.0 m x 0.8 m= 4 m^2 olacak şekilde ayarlanmıştır. Mercimek çeşitlerin parsellere dağılımı tesadüfî olarak gerçekleştirilmiştir. Denemenin ekimleri 25 Nisan 2024 tarihinde tavlı toprağa gerçekleştirilmiştir. Ekimler 20 cm sıra aralığında 2-3 cm sıra üzerinde, her bir sıraya 150-200 adet tohum düşecek şekilde markörle açılan sıralara 3 cm derinliğe elle yapılmıştır. Her parsel 4 sıradan oluşmuştur. Yabancı otlarla mücadele etmek üzere ekimlerle beraber ekim sonrası ve çıkış öncesi yabancı ot ilacı uygulanmış ve tüm vejetasyon süresince 2 sefer çapa yapılmıştır. Her parsele eşit olarak dekara 15 kg DAP (2,7 kg N/da ve 6,9 kg P2O5/da) gübresi ekimle birlikte toprağa verilmiştir. Araştırmanın yürütüldüğü deneme alanındaki çeşitlerin hasadı, hasat olgunluğuna ulaştıkları dönem aralığı olan 25 Temmuz-10 Ağustos 2024 tarihleri arasında el ile yapılmıştır. Parseli oluşturan 4 sıradan her iki yandaki birer sıra ve sıra başlarından 50 cm'nin içerisinde bulunan bitkiler kenar tesiri olarak gözlem dışı bırakılarak bütün işlemler 4 m x 0.4 m = 1.6 m^2'lik alanlar üzerinden yapılmıştır. Her bir parselden hasat edilen bitkiler ayrı ayrı çuvallara konulup etiketlenerek hasat-harman sonrası gerekli ölçümler ve analizler yapılmak üzere Sivas Bilim ve Teknoloji Üniversitesi Tarım Bilimleri ve Teknoloji Fakültesi Tarla Bitkileri Bölümü'nün harman laboratuvarına getirilmiştir. Hasat ve harman işlemleri yapıldıktan sonra her bir yeşil mercimek çeşidine ait 100'er adet tohumda laboratuvar koşullarında su alma kapasitesi (g/tane), su alma indeksi (%), şişme kapasitesi (ml/tane), şişme indeksi (%), kabuk oranı (%) ve protein oranı (%) olmak üzere 6 adet kalite özelliği değerlendirilmiştir.

2.5. Verilerin Değerlendirilmesi

Çalışmadan elde edilen veriler varyans analizine tabi tutulmuş olup kalite özelliklerine ait eldeki veriler arasındaki farklılığın istatistiksel kontrolünde JUMP.13 istatistiki paket programı uygulanmıştır. Önemli çıkanlar arasındaki farklılığın hangi ya da hangilerinden kaynaklandığını belirlemek için ise LSD testi (P>0.05) uygulanmıştır.

3. ELDE EDİLEN BULGULAR ve TARTIŞMA

3.1. Su Alma Kapasitesi (g/tane)

Farklı yeşil mercimek çeşitlerine ait su alma kapasitesi ortalamaları ile istatistik gruplandırmalar Tablo 4'de verilmiş olup varyans analiz sonuçları değerlendirildiğinde yeşil

mercimek çeşitlerinin su alma kapasitesi arasında ki farklar istatistiksel olarak önemli ($p \leq 0.05$) bulunmuştur.

Tablo 4. Yeşil mercimek çeşitlerinde su alma kapasitesi değerlerine ilişkin ortalamalar (g/tane) ile oluşan istatistikî gruplar

Çeşitler	Su Alma Kapasitesi	Çeşitler	Su Alma Kapasitesi
Gümrah	0.059 d	Pul 11	0.071 a
Karagül	0.065 b	Bozok	0.069 a
Kafkas	0.065 b	Meyveci 2001	0.068 ab
Ankara Yeşili	0.055 e	Sultan	0.070 a
Ceren	0.062 c	Çiftçi	0.066 b
Ortalama	0.065		
Önemlilik	*		
CV	6.87		

Tablo 4 incelendiğinde yeşil mercimek çeşitlerine ait su alma kapasitesine ait değerlerin 0.055-0.071 g/tane arasında değişim gösterdiği görülmüş olup Pul 11 çeşidinden su alma kapasitesi bakımından en yüksek (0.071 g/tane) değer elde edilmiştir. Bu çeşitle beraber Sultan (0.070 g/tane) ve Bozok (0.069 g/tane) çeşitleri de aynı grupta (a) yer almıştır. Buna karşın Ankara Yeşili mercimek çeşidi ise 0.055 g/tane su alma kapasitesi değeri ile tüm çeşitler içinde en son sırada yer alırken tüm çeşitlerin su alma kapasite ortalamasının ise 0.065 g/tane olduğu belirlenmiştir. Mercimekte su alma kapasitesi üzerinde yürütülen çalışmada genotiplerin su alma kapasitesi değerlerinin 0,028-0,053 g/tane arasında değişim gösterdiği Özer ve Kaya (2010) tarafından belirlenmiş olup bunun yanında Yozgat'ta yürütülen çalışmada hem yazlık ekimlerde hem de kışlık ekimlerde su alma kapasitesinin yıllara ve çeşitlere göre değiştiği vurgulanmış olup Köse (2018) yılların birleştirilmiş analizlerinde çeşitlere göre su alma kapasitesini yazlık ekimlerde 0,059-0,069 g/tane; kışlık ekimlerde ise 0,031-0,060 g/tane arasında değişen değerler aldığını bildirmiştir.

3.2. Su Alma İndeksi (%)

Su alma kapasitesinin tek tane ağırlığına bölünmesi ile hesaplanan su alma indeksinde her bir genotip için hesaplanan su alma indeksi değeri bir tanenin orijinal ağırlığına göre kaç kat su aldığının göstergesi olarak tanımlanmaktadır (Şehirali ve Atlı, 1993). Yürütülen araştırmada farklı yeşil mercimek çeşitlerine ait su alma indeksi ortalamaları ile istatistik gruplandırmalar Tablo 5'de verilmiş olup su alma indeksi (%) değerlerine ilişkin varyans analiz sonuçları değerlendirildiğinde yeşil mercimek çeşitlerinin su alma indeksi arasında ki farklar istatistiksel olarak çok önemli ($p \leq 0.01$) bulunmuştur.

Tablo 5. Yeşil mercimek çeşitlerinde su alma indeksi değerlerine ilişkin ortalamalar (%) ile oluşan istatistikî gruplar

Çeşitler	Su Alma İndeksi	Çeşitler	Su Alma İndeksi
Gümrah	1.059 b	Pul 11	0.941 f
Karagül	1.045 bc	Bozok	0.918 g
Kafkas	1.033 c	Meyveci 2001	1.008 d
Ankara Yeşili	1.082 a	Sultan	0.931 fg
Ceren	1.024 cd	Çiftçi	0.968 e
Ortalama	1,009		
Önemlilik	**		
CV	7.29		

Yeşil mercimek çeşitlerine ait su alma indeksi değerlerinin %0.918-1.082 arasında değişim gösterdiği görülmüş olup ortalama su alma indeks değerinin ise %1.009 olduğu tespit edilmiştir. Ankara Yeşili mercimek çeşidi su alma indeks değeri bakımından ilk sırada yer alırken bu çeşidi Gümrah (%1.059) ve Kafkas (%1.033) mercimek çeşitleri izlemiş olup Bozok yeşil mercimek çeşidinin ise %0.918 su alma indeks değeri ile tüm çeşitler içinde son sırada yer aldığı ortaya konulmuştur. Kırşehir ekolojik koşullarında bazı yerel yeşil mercimek genotiplerinin kalite özelliklerinin belirlenmesi üzerine yürütülen araştırma sonucunda genotiplerin su alma indeks değerlerinin % 0.894-1.176 arasında değiştiği tespit edilmiş olup ortalama su alma indeks değeri ise %1.066 olarak belirlenmiştir. En yüksek su alma indeksi değeri M31 genotipinde gözlenirken, en düşük değerin ise M1 mercimek genotipinde ortaya konulduğu Sözen ve Karadavut (2019) tarafından saptanmıştır.

3.3. Şişme Kapasitesi (ml/tane)

Farklı yeşil mercimek çeşitlerine ait şişme kapasitesi ortalamaları ile istatistik gruplandırmalar Tablo 6'da verilmiştir. Tablo değerlendirildiğinde yeşil mercimek çeşitlerinin şişme kapasitesi arasında ki farklar istatistiksel olarak önemli bulunmuştur (P<0.05).

Tablo 6. Yeşil mercimek çeşitlerinde şişme kapasitesi değerlerine ilişkin ortalamalar (ml/tane) ile oluşan istatistikî gruplar

Çeşitler	Şişme Kapasitesi	Çeşitler	Şişme Kapasitesi
Gümrah	0.077 bc	Pul 11	0.083 a
Karagül	0.071 c	Bozok	0.079 b
Kafkas	0.083 a	Meyveci 2001	0.070 c
Ankara Yeşili	0.068 cd	Sultan	0.066 d
Ceren	0.059 ef	Çiftçi	0.061 e
Ortalama	0,072		
Önemlilik	*		
CV	6.29		

Çalışmada yer alan yeşil mercimek çeşitlerine ait şişme kapasite değerlerinin 0.059-0.083 ml/tane arasında değişim gösterdiği tespit edilmiştir. Pul 11 ve Kafkas yeşil mercimek çeşitleri şişme kapasitesi bakımından tüm çeşitler içinde ilk sırada yer alırken bu çeşitleri Bozok (0.079 ml/tane) ve Gümrah (0.077 ml/tane) çeşitleri izlemiştir. Çeren çeşidi ise şişme kapasitesi değeri olan 0.059 ml/tane ile son sırada kendine yer bulurken tüm çeşitlere ait şişme kapasite ortalamasının ise 0.072 ml/tane olduğu ortaya konulmuştur. Şişme kapasitesi tohumun suyu almasıyla tohumun bünyesinde bulunan enzimleri aktive ederek biyolojik faaliyetleri çalıştırması açısından önemlidir. Şişme kapasitesi tohumun ekileceği alana göre ayarlanmalıdır.

3.4. Şişme İndeksi (%)

Şişme indeksi, şişme kapasitesi ile önemli ve olumlu ilişki içinde olan bir kalite parametresidir. Şişme kapasitesinin yüksek olması aynı zamanda şişme indeksinin de miktarı hakkında bizlere değerli bilgiler verir. Yürütülen araştırmada farklı yeşil mercimek çeşitlerine ait şişme indeksi ortalamaları ile istatistik gruplandırmalar Tablo 7'de verilmiştir. Tablo değerlendirildiğinde yeşil mercimek çeşitlerinin şişme indeksi değerleri arasında ki farklar istatistiksel olarak çok önemli bulunmuştur (P<0.01).

Tablo 7. Yeşil mercimek çeşitlerinde şişme indeksi değerlerine ilişkin ortalamalar (%) ile oluşan istatistikî gruplar

Çeşitler	Şişme İndeksi	Çeşitler	Şişme İndeksi
Gümrah	2.107 c	Pul 11	1.987 ef
Karagül	2.255 a	Bozok	1.974 efg
Kafkas	2.182 b	Meyveci 2001	2.034 de
Ankara Yeşili	2.045 d	Sultan	1.996 e
Ceren	2.109 c	Çiftçi	1.968 f
Ortalama	2,066		
Önemlilik	**		
CV	6.14		

Çalışmada yer alan yeşil mercimek çeşitlerine ait şişme indeks değerlerinin %1.968-2.255 arasında değişim gösterdiği görülmüştür. Karagül yeşil mercimek çeşidi %2.255 şişme indeksi değeri ile ilk sırada yer alırken bu çeşidi %2.182 ile Kafkas ve %2.107 ile Gümrah çeşitleri izlemiş olup tüm çeşitlere ait şişme indeksi ortalamasının ise %2.066 olduğu tespit edilmiştir. Bunun yanında Çiftçi yeşil mercimek çeşidi ise almış olduğu %1.968 şişme indeksi değeri ile tüm çeşitler içinde son sırada yer almıştır.

3.5. Kabuk Oranı (%)

Farklı yeşil mercimek çeşitlerine ait kabuk oranı ortalamaları ile istatistik gruplandırmalar Tablo 8'de verilmiş olup Tablo değerlendirildiğinde yeşil mercimek çeşitlerinde kabuk oranı arasında ki farklar istatistiksel olarak çok önemli bulunmuştur ($P<0.01$).

Tablo 8. Yeşil mercimek çeşitlerinde kabuk oranı değerlerine ilişkin ortalamalar (%) ile oluşan istatistikî gruplar

Çeşitler	Kabuk Oranı	Çeşitler	Kabuk Oranı
Gümrah	8.87 d	Pul 11	7.48 h
Karagül	8.94 c	Bozok	9.68 a
Kafkas	7.82 g	Meyveci 2001	8.23 f
Ankara Yeşili	9.36 b	Sultan	8.59 ef
Ceren	7.29 hı	Çiftçi	8.63 e
Ortalama	8,49		
Önemlilik	**		
CV	4.92		

Yeşil mercimek çeşitlerinden elde edilen kabuk oranı değerleri %7.29-9.68 arasında değişim göstermiş olup en yüksek kabuk oranı değeri Bozok yeşil mercimek çeşidinden (%9.68) elde edilirken bu çeşidi sırayla Ankara yeşili (%9.36) ve Karagül (%8.94) çeşitleri izlemiş olup tüm yeşil mercimek çeşitlerine ait kabuk oranı ortalamasının ise %8.49 olduğu belirlenmiştir. Bunun yanında Ceren çeşidi ise almış olduğu %7.29 şişme indeksi değeri ile tüm çeşitler içinde son sırada yer almıştır. Kabuk oranı tohumun su ve hava almasında en önemli etkenlerin başında gelmektedir. Tohum kabuğunun kalın ya da ince olması aynı zamanda tohumun ortamdaki sudan faydalanma miktarını ve hızını etkileyecektir. Bunun için kabuk oranlarının bilinmesi özellikle çimlenmenin ve çıkışın güçlü olabilmesi için gereklidir. Kırşehir ekolojik koşullarında bazı yerel yeşil mercimek genotiplerinin kalite özelliklerinin belirlenmesi üzerine yürütülen

araştırma sonucunda genotiplerin kabuk oranı değerlerinin %7.00-10.23 arasında değiştiği Sözen ve Karadavut (2019) tarafından tespit edilmiş olup ortalama kabuk oranı değeri ise %8.59 olarak belirlenmiştir.

3.6. Protein Oranı (%)

Farklı yeşil mercimek çeşitlerine ait protein oranı ortalamaları ile istatistik gruplandırmaların verildiği Tablo 9 değerlendirildiğinde yeşil mercimek çeşitlerinin protein oranı arasında ki farklar istatistiksel olarak çok önemli bulunmuştur (P<0.01).

Tablo 9. Yeşil mercimek çeşitlerinde protein oranı değerlerine ilişkin ortalamalar (%) ile oluşan istatistikî gruplar

Çeşitler	Protein Oranı	Çeşitler	Protein Oranı
Gümrah	29.64 a	Pul 11	25.62 de
Karagül	28.49 b	Bozok	25.41 def
Kafkas	27.15 c	Meyveci 2001	24.27 e
Ankara Yeşili	26.88 cd	Sultan	23.77 ef
Ceren	26.09 d	Çiftçi	23.05 f
Ortalama	26.04		
Önemlilik	**		
CV	5.07		

Yürütülen araştırmada ele alınan yeşil mercimek çeşitlerine ait protein oranı değerlerinin %23.05-29.64 arasında değişim gösterdiği tespit edilmiştir. Protein oranı en yüksek Gümrah yeşil mercimek çeşidinden elde edilirken bu çeşidi Karagül (%28.49) ve Kafkas (%27.15) çeşitleri izlemiş olup tüm çeşitlere ait protein oranı ortalamasının ise %26.04 olduğu belirlenmiştir. Buna karşın Çiftçi yeşil mercimek çeşidinin ise %23.05 protein oranı değeri ile tüm yeşil mercimek çeşitleri içinde son sırada yer aldığı görülmüştür. Yeşil mercimek çeşitlerinin protein oranlarının çeşitli faktörlere bağlı olarak değiştiği ifade edilmekte olup bu faktörlerin başında iklim ve toprak faktörleri ile kültürel uygulamalar ve yetiştirme şartları gelmektedir. Aynı zamanda değişik şartlarda yetiştirilen yeşil mercimek çeşitlerinin protein oranlarının farklı olduğu belirtilmektedir (Önder, 1992). Yemeklik baklagil türleri arasında mercimeğin protein içeriği (%23-31) diğer türlere göre oldukça yüksek olup insan beslenmesi için önemi oldukça fazladır (Du ve ark., 2014; Zulkadir ve ark., 2015). Mercimekte protein oranının kalıtım derecesinin yüksek olmasının yanında protein oranı iklimsel faktörler ve yetiştirme tekniği paketi içinde yer alan uygulamalara göre önemli oranda değişiklik gösterebilmektedir (Çölkesen ve ark., 2005). Farklı mercimek genotipleri ile yürütülen çalışmalarda genotiplere göre protein oranının Arabistan yarımadasında ortalama %27,35 (Alghamdi ve ark., 2014); Pakistan'da ise %28,8-30,6 (Zia-Ul-Haq ve ark., 2011) arasında değişim gösterdiği saptanmıştır. Konya'da yürütülen çalışmada mercimekte en yüksek protein oranının Seyran-96 çeşidinde (%26,9) belirlendiği bunu Fırat-87, Çiftçi ve Özbek çeşitlerinin izlediği Hakkoymaz (2018) tarafından rapor edilmiştir. Yozgat koşullarında yürütülen bir başka çalışmada ise protein oranları bakımından mercimek çeşitlerinin protein oranın kışlık ekimlerde %27.7-30.4 arasında değişim gösterdiği Köse (2018) tarafından tespit edilmiştir.

4. SONUÇ

Farklı yeşil mercimek çeşitlerinin bazı teknolojik özelliklerinin ortaya konulması amacıyla Sivas ekolojik koşullarında yürütülen araştırma sonucunda su alma ve şişme kapasitesi özellikleri hariç bütün teknolojik özellikler bakımından yeşil mercimek çeşitlerinin arasında %1 düzeyinde önemli farklılıklar bulunmuştur. Araştırma içinde yer alan yeşil mercimek

çeşitlerinde ortaya konulan bu farklılıkların çeşitlerin genetik özelliklerinin yanında yetiştiriciliği yapılan bölgelerin iklimsel faktörlerinden de kaynaklanabileceği tahmin edilmektedir. Yürütülen araştırmada birçok kalite özelliklerinden dolayı Pul 11, Gümrah ve Ceren çeşitlerinin diğer yeşil mercimek çeşitlerine nazaran öne çıktıkları ortaya konulmuştur.

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MERCİMEK ISLAHINA YÖNELİK GENOMİK VE TRANSKRİPTOMİK YAKLAŞIMLAR

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Özet

Mercimek (*Lens culinaris* Medik.), yüksek besin değeri ve sürdürülebilir tarıma katkısı nedeniyle dünya genelinde önemli bir baklagil türüdür. Ancak mercimek üretimi; kuraklık, sıcaklık, tuzluluk gibi abiyotik stresler ile fungal ve bakteriyel hastalıklar gibi biyotik etmenler nedeniyle ciddi verim kayıplarıyla karşı karşıyadır. Klasik ıslah yöntemleri, bu karmaşık stres koşullarına dayanıklılığın geliştirilmesinde sınırlı kalmakta; bu durum moleküler temelli yaklaşımların önemini artırmaktadır. Son yıllarda yeni nesil dizileme (NGS) teknolojilerindeki gelişmeler, mercimekte genomik ve transkriptomik analizlerin yaygın biçimde kullanılmasını sağlamıştır. RNA-Seq tabanlı transkriptomik çalışmalar, stres koşulları altında gen ifade profillerinin ortaya konmasına, fonksiyonel genlerin tanımlanmasına ve aday gen bölgelerinin belirlenmesine olanak tanımaktadır. Ayrıca genomik seleksiyon (GS) yaklaşımları, genom çapında belirteç verilerini kullanarak erken jenerasyonlarda üstün genotiplerin tahmin edilmesini mümkün kılmakta ve ıslah süresini önemli ölçüde kısaltmaktadır. Bu çalışmada, mercimek ıslahında genomik ve transkriptomik yaklaşımların mevcut durumu, RNA-Seq uygulamaları ve genomik seleksiyonun entegrasyonu ele alınmış; bu yaklaşımların stres toleransı yüksek, verimli ve iklim değişikliğine uyumlu çeşitlerin geliştirilmesindeki potansiyeli değerlendirilmiştir. Elde edilen bulgular, çoklu omik veri entegrasyonunun mercimek ıslahında geleceğe yönelik stratejik bir araç olduğunu göstermektedir.

Anahtar Kelimeler: Lens culinaris, RNA-Seq, transkriptomik analiz, genomik seleksiyon, stres toleransı

GENOMIC AND TRANSCRIPTOMIC APPROACHES FOR LENTIL BREEDING

Abstract

Lentil (*Lens culinaris* Medik.) is one of the most important grain legumes worldwide due to its high nutritional value and contribution to sustainable agricultural systems. However, lentil production is severely constrained by abiotic stresses such as drought, heat, and salinity, as well as biotic stresses including fungal and bacterial diseases. Conventional breeding approaches often remain insufficient to address these complex stress factors, highlighting the need for molecular-based strategies. Recent advances in next-generation sequencing (NGS) technologies have enabled extensive genomic and transcriptomic analyses in lentil. RNA-Seq–based transcriptomic studies provide comprehensive insights into gene expression dynamics under stress conditions, facilitating the identification of functional genes and candidate genomic regions associated with stress tolerance. In parallel, genomic selection (GS) approaches utilize genome-wide marker information to predict breeding values, allowing the identification of superior genotypes at early generations and significantly reducing breeding cycle duration. This study reviews the current status of genomic and transcriptomic applications in lentil breeding, with particular emphasis on RNA-Seq analyses and the integration of genomic selection. The findings highlight the potential of combining multi-omics data to accelerate the development of high-yielding, stress-tolerant, and climate-resilient lentil cultivars.

Keywords: *Lens culinaris*, RNA-Seq, transcriptomics, genomic selection, stress tolerance

1. Giriş

Mercimek (Lens culinaris Medik.), Fabaceae familyasının Fabeae ailesine ait, diploid (2n=2x=14) ve kendine döllenen bir bitkidir. Tarımsal üretim açısından dünyanın en eski kültür bitkilerinden biridir. Arkeobotanik veriler, mercimeğin kültüre alınışının yaklaşık 8.000-9.000 yıl önce Bereketli Hilal bölgesinde (Türkiye, Suriye ve Irak çevresi) başladığını göstermektedir. Günümüzde mercimek, Asya kıtasında Hindistan, Kanada, Türkiye ve Avustralya başta olmak üzere 70'ten fazla ülkede yetiştirilmekte olup dünya genelinde yıllık yaklaşık 7,6 milyon hektar ekim alanı ve 6,8 milyon ton üretim hacmine ulaşmaktadır. Mercimek, hem insan beslenmesi hem de sürdürülebilir tarımsal sistem açısından önemli bir baklagildir. Tohumlarının yüksek ham protein içeriği (%22-36), zengin lif içeriği (%8-10), karbonhidratlar ve fonksiyonel fitokimyasallar (fenolik bileşikler, flavonoidler, fitosteroller) bakımından zengin olması, onu gelişmekte olan ülkelerde bitkisel protein güvenliğinin temel kaynaklarından biri yapmaktadır. Aynı zamanda kök nodüllerinde yaşayan Rhizobium leguminosarum bakterileri aracılığıyla atmosferik azotu fikse etmesi, sürdürülebilir tarım sistemlerinde toprak verimliliğini artıran önemli bir unsurdur. Bununla birlikte mercimek üretimi, kuraklık, yüksek sıcaklık, tuzluluk ve düşük sıcaklık gibi abiyotik streslerle, antraknoz (Colletotrichum truncatum), Fusarium solgunluğu (F. oxysporum f.sp. lentis) ve kök çürüklüğü (Rhizoctonia bataticola) gibi biyotik etmenlerle sınırlanmaktadır. Bu stres faktörleri, özellikle Güney Asya ve Orta Doğu ekosistemlerinde %30-70 oranına kadar verim kayıplarına neden olabilmektedir. Klasik ıslah yöntemleri, son dönemlerde iklimsel değişikliklere bağlı olarak daha da şiddetini artıran abiyotik ve biyotik stres koşullarına dayanıklılık/toleranslılık gen kaynaklarının belirlenmesinde, yetersiz kalabilmektedir. Bu nedenle moleküler düzeyde yeni yaklaşımlar geliştirilmesi zorunlu hale gelmiştir (Singh ve ark., 2017; Kumar ve ark., 2021). Güncel genomik analizler ve dizileme teknolojilerindeki ilerlemeler, mercimek genomunun yapısal ve fonksiyonel özelliklerinin ayrıntılı biçimde ortaya konmasına olanak tanımıştır. Bu durum, mercimek ıslahında moleküler belirteç temelli seleksiyon ve genetik haritalama çalışmalarının önemini ve etkinliğini önemli ölçüde artırmıştır. Genomik veri setleri, ıslah programlarında moleküler markör geliştirme, QTL haritalama, genomik seleksiyon (GS) ve transkriptomik analiz uygulamalarına temel oluşturmuştur. Özellikle transkriptomik yaklaşımlar, çevresel stres koşullarına dayanıklılık/toleranslılık konusunda genlerin nasıl ifade edildiğini ortaya koymada yeni ufuklar açmıştır. RNA-seq tabanlı çalışmalarda, kuraklık, sıcaklık ve tuzluluk stresleri altında antioksidan savunma sistemleri (SOD, CAT, POD), ABA bağımlı sinyal mekanizması, ısı şok proteinleri (HSPs) ve LEA proteinleri gibi çok sayıda genin farklı düzeylerde ifade edildiği gösterilmiştir. Bu bulgular, abiyotik ve biyotik stres koşullarına tolerans mekanizmasının poligenik doğasını açıklığa kavuştururken, aynı zamanda fonksiyonel genlerin belirlenmesine ve ıslah hedeflerinin tanımlanmasına olanak tanımıştır. Bu bağlamda, mercimek ıslahında genomik ve transkriptomik verilerin birleştirilmesi, klasik yöntemlerin ötesine geçerek daha hızlı, hedefe yönelik ve çevreye duyarlı bir ıslah süreci sağlamaktadır. Yeni nesil dizileme (NGS), genotipleme teknikleri (GBS, DArTseq), yüksek yoğunluklu SNP panelleri, RNA-Seq ve çoklu omik veri entegrasyonu gibi modern teknolojiler sayesinde mercimek, artık yalnızca yüksek protein içeriğiyle değil, aynı zamanda iklim değişikliğine karşı dayanıklılığıyla da öne çıkan model bir baklagil türü olarak değerlendirilmektedir (Singh ve ark., 2019; Wang ve ark., 2020; Demir ve Bakır, 2022).

2. Mercimek Genomu Üzerine Güncel Gelişmeler

Mercimek (*Lens culinaris Medik.*), yaklaşık 4,0 Gbp büyüklüğünde bir genoma sahip olup, baklagiller arasında en geniş genom boyutlarından birine sahiptir. Genomun yaklaşık %70-75'i tekrarlayan DNA dizilerinden oluşmaktadır. Tekrarlayan dizilerin yüksek oranda bulunması,

özellikle transpozon elementlerinin fazlalığından kaynaklanmakta olup, bu durum dizilimde karmaşıklığı artırmaktadır. Fonksiyonel analizler, genlerin önemli bir bölümünün transkripsiyon faktörleri (bZIP, MYB, NAC, WRKY), stres tepkisiyle ilişkili genler (LEA, DREB, HSP) ve metabolik yol enzimleri (glikoliz, fenilpropanoid ve flavonoid biyosentezi) ile bağlantılı olduğunu ortaya koymuştur. Özellikle transkripsiyon faktörleri ile hastalık direnci genlerinin (NBS-LRR, TIR-NBS) yoğunlaştığı bölgelerin, kromozom 2, 4 ve 6 üzerinde kümelendiği belirlenmiştir. Referans genomun oluşturulması, mercimeğin genetik yapısı ve genom yapısına ilişkin önemli bilgiler sağlamış, QTL haritalama, SNP paneli geliştirme, genomik seleksiyon (GS) ve fonksiyonel gen belirleme çalışmalarına güçlü bir temel oluşturmuştur. Bu kapsamda, referans genom verisi gelecekte yürütülecek ıslah ve fonksiyonel genomik araştırmaları için kilit bir kaynak niteliği taşımakta ve türün genetik iyileştirme potansiyelini önemli ölçüde artırmaktadır (Ogutcen, 2018; Topu ve ark., 2023).

2.1. Mercimek Gen Havuzunun Genişletilmesinde Yabani Türlerin Önemi

Mercimeğin kültüre alınmış formu (*L. culinaris Medik.*), genetik olarak *L. culinaris subsp. orientalis* ile en yakın akrabadır ve bu alt tür, günümüzde genetik varyasyonun arttırılmasında önemli bir kaynak olarak değerlendirilmektedir. Ayrıca, *L. ervoides*, *L. nigricans* ve *L. lamottei* gibi yabani mercimek türleri, özellikle abiyotik ve biyotik stres koşullarına tolerans/dayanıklılık genlerinin belirlenmesinde önemli kaynaklar olarak kullanılmaktadır. Kapsamlı yeniden dizileme çalışmaları, *Lens ervoides* genomunun, kültürü yapılan mercimeğe göre daha yüksek düzeyde allelik çeşitlilik ve özellikle hastalık ve zararlılara karşı daha geniş bir dayanıklılık/toleranslılık gen kaynağına sahip olduğunu göstermiştir. Bu bulgu, yabani türlerin genetik çeşitliliğinin, ıslah programlarında değerlendirilebilecek önemli bir kaynak olduğunu ortaya koymaktadır. Ayrıca *L. ervoides* ve diğer yabani türlerde belirlenen bazı gen bölgeleri, özellikle RGA2, SWEET11 ve FAD2 genleri, kuraklık toleransı, lipid metabolizması ve şeker taşınımı gibi önemli fizyolojik ve biyokimyasal süreçlerle ilişkilendirilmiştir. Bu genlerin işlevsel olarak incelenmesi, mercimek ıslahında stres toleransı ve verim potansiyelini artırmaya yönelik yeni aday genlerin tanımlanmasına katkı sağlayabilecektir. Bu nedenle, yabani mercimek türlerinin genomik karakterizasyonu, mevcut gen havuzunun genişletilmesi ve iklim değişikliğine uyumlu, dirençli çeşitlerin geliştirilmesi açısından stratejik bir öneme sahiptir (Gutierrez-Gonzalez ve ark., 2022; Liber ve ark., 2021; Coyne ve ark., 2013).

Tek bir referans genomun tüm genetik varyasyonu temsil edemeyeceği anlayışıyla, 2022 yılından itibaren mercimek için tüm genetik çeşitliliği kapsayan çekirdek koleksiyon oluşturma çalışmaları hız kazanmıştır. Khazaei ve ark. (2016), *L. culinaris*'in farklı coğrafi kökenlerinden 20 genotipi içeren bir çekirdek genom veri seti oluşturmuş ve toplamda yaklaşık 47.000 gen bölgesi tanımlamıştır. Bu genlerin %80'inin çekirdek genomda, geri kalanının ise ek ve özel genlerde yer aldığı bildirilmiştir. Bu özel genlerin çoğu, abiyotik stres koşullarına, sekonder metabolit sentezi ve savunma mekanizmalarıyla ilişkilidir. Ayrıca pangenom (tüm genetik çeşitliliği kapsayan analiz), Asya ve Akdeniz orijinli genotipler arasında gen kayıpları ve kazançları bulunduğunu göstermiştir. Bu durum, adaptasyonun genomik temelini açıklamak açısından büyük önem taşımaktadır.

Karşılaştırmalı genomik analizlerde ise mercimek, diğer baklagil türleri olan nohut (*Cicer arietinum*), bezelye (*Pisum sativum*) ve soya (*Glycine max*) genomlarıyla karşılaştırılmıştır. Sonuçlar, türler arasında yüksek düzeyde korunmuş kromozomlar üzerindeki benzer gen dizilimleri bulunduğunu ve bu bölgelerin özellikle azot fiksasyonu, fenilpropanoid metabolizması ve stres koşullarına dayanıklılık/toleranslılık ile ilişkili genlerde korunduğunu ortaya koymuştur. Bu durum, mercimek ve yakın akraba türlerde temel metabolik ve fizyolojik süreçlerin evrimsel olarak korunmuş olduğunu, dolayısıyla bu gen bölgelerinin adaptasyon ve dayanıklılık mekanizmalarında kritik bir rol oynadığını göstermektedir (Karagül, 2017).

2.4. Fonksiyonel Genomik ve Veri Kaynakları

Mercimek genomik araştırmalarında son yıllarda kaydedilen ilerlemeler, çok sayıda açık erişimli veri tabanının oluşturulmasını sağlamıştır. Bu platformlar, mercimek ıslahı ve fonksiyonel genetik çalışmalarında araştırmacılara kapsamlı bilgi sunan önemli biyoinformatik referans merkezleri haline gelmiştir. Mercimek genomik araştırmalarını destekleyen belli başlı veri platformları aşağıda özetlenmiştir.

LENSBASE (ICARDA, 2022): Mercimeğe özgü genom, transkriptom ve moleküler marker (SSR, SNP, DArT vb.) verilerinin bütünleştirildiği kapsamlı bir platformdur. Kullanıcılar, farklı çeşitler arasında gen karşılaştırması yapabilir, dizi analizi gerçekleştirebilir ve ıslah çalışmalarında kullanılabilecek aday genleri tanımlayabilirler.

Legume Information System (LIS): Nohut, bezelye, bakla ve mercimek dahil olmak üzere 25 baklagil türüne ait genom anotasyonları, gen aileleri, QTL (nicel özellik lokusu) haritaları ve protein dizilerini içeren geniş kapsamlı bir veri tabanıdır. LIS, türler arası karşılaştırmalı genom analizleri yapılmasına olanak tanıyarak genetik evrim ve fonksiyonel çeşitlilik çalışmalarını desteklemektedir.

LIS-GEA (Genome-Environment Association Portal): Genotip × çevre etkileşimlerini analiz etmek üzere geliştirilmiş özel bir alt platformdur. Bu sistem, farklı çevre koşullarına adaptasyon gösteren lokusların ve allel varyantlarının belirlenmesine yardımcı olur. Böylece çevresel stres faktörlerine dayanıklılıkla ilişkili gen bölgelerinin tanımlanmasını kolaylaştırır.

Bu platformlar aracılığıyla elde edilen genomik ve transkriptomik veriler, mercimek ıslahında önemli uygulama alanları bulmaktadır. Özellikle aday gen tanımlama, gen dizilim varyasyonlarını inceleme, markör destekli seleksiyon (MAS) ve genomik seleksiyon (GS) modellerinde elde edilen sonuçların doğruluğunu ve öngörü gücünü artırmaktadır. Bu durum, ıslah programlarının daha hedefe yönelik, hızlı ve veri temelli şekilde yürütülmesine katkı sağlamaktadır (Pfeiffer ve ark., 2016; Berendzen ve ark., 2021; Sanderson ve ark., 2019).

3.2. Genomik Seleksiyon (GS)

Genomik seleksiyon (GS), ilk kez Meuwissen ve arkadaşları tarafından ortaya konulmuş bir ıslah stratejisidir (de Koning, 2016). Bu yaklaşım, tüm genom boyunca dağılım gösteren moleküler markörlerin bir bireyin genetik değerini tahmin etmek amacıyla istatistiksel ve matematiksel modellere entegre edilmesi esasına dayanmaktadır. Başka bir ifadeyle, genomik seleksiyon, her bir markörün etkisini ayrı ayrı değerlendirmek yerine, genomun tamamını kapsayan bütüncül bir tahmin modeli oluşturmaktadır. Bu yöntem, klasik marker destekli seleksiyondan (MAS) farklı olarak yalnızca belirli gen bölgelerine değil, tüm genomdaki varyasyonlara dayanır. Böylece, karmaşık ve çok genli karakterlerin (verim, biyotik/abiyotik stres toleransı, kalite özellikleri vb.) toplam genetik katkısı daha doğru bir şekilde tahmin edilebilmektedir.

Mercimek ıslahında genomik seleksiyonun temel amacı, fenotipleme gibi zaman alıcı ve maliyetli süreçleri azaltmak, bunun yerine genotipik veriler üzerinden yüksek doğrulukla tahmin yaparak ıslah döngüsünü hızlandırmaktır. Bu sayede, bir genotipin fenotipik performansı değerlendirilmeden önce, genomik veriler aracılığıyla üstün bireyler seçilebilmektedir. Genomik seleksiyon modellerinde, genotipik veriler geniş popülasyonlardan elde edilen referans setleri ile ilişkilendirilir. Bu setlerde hem genotipik hem de fenotipik veriler yer almaktadır. Model, bu referans popülasyondan öğrendiği istatistiksel ilişkileri kullanarak yeni bireylerin genetik değerlerini yüksek doğrulukla tahmin edebilmektedir. Sonuç olarak, genomik seleksiyon mercimek gibi uzun jenerasyon süresine sahip bitkilerde, ıslah döngüsünü kısaltarak daha hızlı, veriye dayalı ve hedefe yönelik bir ıslah süreci yürütülmesini mümkün kılmaktadır (Meuwissen ve ark., 2001; Gouache ve ark., 2013; Crossa ve ark., 2017).

Genomik seleksiyon uygulamalarında, genetik verilerden en yüksek tahmin doğruluğunu elde edebilmek için farklı istatistiksel ve makine öğrenmesi temelli modeller kullanılmaktadır. Mercimek ıslahında yaygın olarak başvurulan başlıca modeller şunlardır:

- ✓ RR-BLUP (Ridge Regression Best Linear Unbiased Prediction): Genomik marker'ların etkilerini sabit bir varyans varsayımı altında tahmin eden en temel genomik seleksiyon modellerinden biridir. Çok sayıda marker bulunduğunda aşırı uyumu engelleyerek güvenilir tahminler sağlamaktadır.
- ✓ GBLUP (Genomic Best Linear Unbiased Prediction): RR-BLUP'un genetik benzerlik matrisine dayalı bir türevidir. Genotipler arası genomik ilişkileri kullanarak bireylerin genetik değerlerini tahmin etmektedir. Bu model, hem doğruluk hem de işlem kolaylığı açısından mercimek gibi çok genli karakterlere sahip türlerde sıklıkla tercih edilmektedir.
- ✓ Bayesyen Modeller (BayesA, BayesB, BayesCπ): Marker etkilerinin dağılımını olasılıksal temelde tahmin eden esnek modellerdir. Marker etkilerinin sabit olmadığı, bazı marker'ların büyük etkiye sahip olduğu durumlarda üstün performans göstermektedir.
- ✓ Makine Öğrenmesi Yaklaşımları (Random Forest - RF, Support Vector Machine - SVM): Marker verilerindeki karmaşık ve doğrusal olmayan ilişkileri yakalamada etkilidir. Bu modeller, özellikle gen × çevre etkileşimlerinin önemli olduğu özelliklerde tahmin doğruluğunu artırabilmektedir (Hickey ve ark., 2017; Javid ve ark., 2020).

Mercimekte yapılan çeşitli çalışmalar, bu modellerin ıslah sürecinde önemli avantajlar sağladığını göstermektedir. GBLUP modeli kullanılarak mercimek genotiplerinde tane verimi, çiçeklenme süresi ve biyotik stres toleransı tahmin edilmiştir. Elde edilen sonuçlara göre, genomik seleksiyon modelleri, klasik seleksiyon yöntemlerine kıyasla %25-40 oranında daha yüksek tahmin doğruluğu sağlamıştır. Bir başka çalışmada, kuraklık ve tuzluluk stresine dayanıklılıkla ilişkili GS modelleri oluşturulmuştur. Bu modellerde, DREB2, NHX1 ve SOS1 gen bölgeleriyle ilişkili SNP setlerinin modele dahil edilmesi, tahmin performansını belirgin biçimde artırmıştır. Bu bulgular, genomik seleksiyonun özellikle stres toleransı ve verim stabilitesi gibi karmaşık karakterlerin ıslahında güçlü bir araç olarak kullanılabileceğini göstermektedir (Haile ve ark., 2020; Gebremedhin ve ark., 2024). Sonuç olarak, mercimek ıslahında kullanılan genomik seleksiyon modelleri, genetik verilerle fenotipik performans arasındaki ilişkiyi yüksek doğrulukla ortaya koymakta, böylece ıslah süresini kısaltmakta ve verim, kalite ile dayanıklılık özelliklerinin genetik olarak geliştirilmesine katkı sağlamaktadır.

3.2.1. Genomik Seleksiyonun Islah Programlarına Entegrasyonu

Genomik seleksiyon, klasik ıslah yöntemlerine kıyasla ıslah sürecini önemli ölçüde kısaltan yenilikçi bir yaklaşımdır. Mercimek ıslahında uygulanan genomik seleksiyon modelleri sayesinde, geleneksel olarak 6-8 yıl süren bir ıslah süreci, genetik tahmine dayalı seçim yöntemleriyle 3-4 yıla kadar indirilebilmektedir. Bu durum, hem zaman hem maliyet açısından önemli bir avantaj sağlamaktadır. Genomik seleksiyonun ıslah programlarına entegrasyonu, farklı aşamalarda çeşitli olanaklar sunmaktadır.

Erken jenerasyon seleksiyonu (F_2-F_4): Genomik tahmin modelleri kullanılarak melezleme popülasyonlarında, bitkiler olgunlaşmadan önce üstün genotipler belirlenebilmektedir. Bu, erken dönemde istenen özelliklere sahip hatların seçilmesini ve sonraki jenerasyonlara aktarılmasını kolaylaştırmaktadır.

Stres koşullarında dayanıklılık tahmini: Genomik seleksiyon modelleri, genotip × çevre etkileşimini dikkate alarak kuraklık, tuzluluk veya hastalık gibi stres faktörlerine dayanıklı hatların bilgisayar ortamında değerlendirilmesine olanak tanımaktadır. Böylece saha denemeleri öncesinde, stres toleransı yüksek genotipler belirlenebilmektedir.

Genetik kazancın artırılması: Genomik seleksiyon, her ıslah sürecinde tahmin doğruluğunu artırarak birim zaman başına genetik kazanç oranını yükseltmektedir. Bu sayede, hedeflenen özelliklerde hızlı ilerleme sağlanabilir ve popülasyon ortalaması sürekli iyileştirilebilir.

Günümüzde genomik seleksiyon, Kanada, Hindistan ve Avustralya gibi mercimek üretiminde öncü ülkelerde yürütülen ıslah programlarında yaygın olarak kullanılmaktadır. Bu ülkelerde genomik seleksiyon; verim, biyotik stres direnci ve tane kalite özelliklerinin iyileştirilmesinde standart bir karar destek aracı olarak uygulanmaktadır. Bu gelişmeler, genomik seleksiyonun sadece bir tahmin yöntemi değil, aynı zamanda modern ıslah programlarının dijital dönüşümünü destekleyen stratejik bir araç haline geldiğini göstermektedir. Uzun vadede, mercimek ıslahında genomik seleksiyonun fenotipleme verileriyle birlikte çoklu omik (genomik, transkriptomik, metabolomik) verilerle entegre edilmesi, daha hassas, hızlı ve çevreye uyumlu çeşit geliştirme süreçlerinin önünü açacaktır **(**Crossa ve ark., 2017; Varshney ve ark., 2017; Voss-Fels ve ark., 2019; Javid ve ark., 2020; Meuwissen ve ark., 2001)**.**

4. Transkriptomik Verilerin Islah Programlarına Entegrasyonu

Genomik çalışmaların sunduğu yapısal bilgiyi tamamlayıcı nitelikte olan transkriptomik analizler, mercimek (*Lens culinaris* Medik.) ıslahında gen ifadesi düzeyindeki değişimlerin anlaşılması, stres yanıtlarının çözülmesi ve fonksiyonel genlerin tanımlanması açısından kritik bir rol oynamaktadır. Transkriptomik veriler, yalnızca genlerin varlığını değil, aynı zamanda bu genlerin hangi çevresel koşullarda, hangi doku veya gelişim evresinde ve hangi düzeyde aktive olduğunu ortaya koymaktadır. Yeni nesil dizileme teknolojilerindeki gelişmeler sayesinde, RNA-Seq yöntemi mercimek bitkisinin gen ifadelerini çok daha ayrıntılı bir şekilde analiz edebilmektedir. RNA-Seq, bir organizmanın belirli bir anda hücrelerinde aktif olarak çalışan tüm genleri (transkriptom) ortaya çıkarmakta ve genlerin ne düzeyde ifade edildiğini göstermektedir. Bu yöntem, eski tekniklerle tespit edilemeyen düşük miktardaki genlerin ve farklı ekson yapısına sahip gen varyantlarının da belirlenmesini sağlamaktadır.

RNA-Seq verileri, mercimek ıslahında iki farklı şekilde kullanılmaktadır. Bunlardan biri referans genoma dayalı hizalama, diğeri ise de novo montaj adı verilen, mevcut bir referans genom olmadan gen dizilerinin sıfırdan birleştirilmesi yöntemidir. Referans tabanlı hizalama yöntemleri, bilinen genom dizilerine dayanarak gen ekspresyon seviyelerini nicel olarak ölçmeyi sağlamaktadır. De novo montaj ise referans genomun bulunmadığı durumlarda transkript dizilerinin doğrudan birleştirilmesiyle yeni gen bölgelerini tanımlamaktadır. Bu yaklaşımlar sayesinde mercimekte kuraklık, tuzluluk, sıcaklık stresi ve hastalık etmenlerine karşı verilen transkripsiyonel yanıtlar detaylı biçimde ortaya konmuştur. Ayrıca farklı gelişim evrelerinde gen ekspresyon profillerinin incelenmesi, verim ve kaliteye etki eden genlerin belirlenmesine katkı sağlamaktadır. Transkriptomik verilerin bu şekilde kullanılması, ıslah programlarında aday gen tanımlama, biyotik ve abiyotik stresle ilişkili gen ağlarını modelleme ve markör geliştirme (SNP, SSR) gibi çok sayıda uygulamaya temel oluşturmaktadır. Sonuç olarak, transkriptom analizleri, mercimek ıslahında genomik seleksiyonun tamamlayıcısı olarak görev yapmakta, çevresel koşullara duyarlı, yüksek verimli ve stres toleransı yüksek genotiplerin geliştirilmesine bilimsel zemin hazırlamaktadır (Singh ve ark., 2019).

4.1. Mercimekte Gen İfadesinin RNA-Seq Analizi ile Karakterizasyonu

RNA-Seq teknolojisi, mercimek genotiplerinde farklı abiyotik (kuraklık, soğuk, tuzluluk vb) ve biyotik (hastalık etmenleri) streslere verilen moleküler yanıtların belirlenmesinde en güçlü araçlardan biridir. Bu yöntem, stres koşullarında hangi genlerin etkili olduğunu tespit ederek tolerans mekanizmalarının anlaşılmasına katkı sağlamaktadır (Sohrabi ve ark., 2022).

Singh ve ark. (2017), kuraklığa dayanıklı (*PDL-1*) ve hassas (*JL-3*) mercimek genotiplerini karşılaştırarak 4.812 adet farklı ifade edilen gen (DEG) belirlemiştir. Bu genler arasında özellikle antioksidan savunma enzimleri (*APX, CAT, SOD),* osmotik koruma sağlayan metabolizma genleri (*proline dehydrogenase, betaine aldehyde dehydrogenase)* ve ABA (absisik asit) sinyal yolu bileşenleri (*NCED3, PYR/PYL, SnRK2)* ön plana çıkmıştır. Bu sonuçlar, kuraklık stresine karşı mercimeğin Reaktif oksijen türlerini (ROS) azaltma, ABA

aracılı stres sinyallemesi ve hücre içi su dengesini koruma gibi üç temel mekanizma kullandığını göstermektedir.

Soğuk stresine yönelik çalışmalarda da benzer moleküler yanıtlar görülmektedir. Barrios ve ark. (2017), düşük sıcaklığa maruz kalan mercimek bitkilerinde CBF/DREB transkripsiyon faktörlerinin ve soğuk yanıtlı COR genlerinin belirgin şekilde arttığını saptamıştır. Bu genler, bitkinin erken dönem soğuk tepkisinin en önemli düzenleyicileridir. RNA-Seq analizleri yalnızca stres yanıtında değil, aynı zamanda gelişimsel süreçlerde de değerli bilgiler sağlar. Mercimek tohum gelişimi boyunca yaptıkları çalışmada karbonhidrat metabolizması genlerinin (*AGPase, SUSY*) ve tohum protein depolama genlerinin (*legumin, vicilin, albümin* vb) yüksek düzeyde ifade edildiğini göstermiştir. Bu bulgular, tohum kalitesi ve besin değeri açısından kritik gen ağlarının tanımlanmasına önemli katkılar sağlamaktadır (Dutta ve ark., 2022; Song ve ark., 2022).

4.2. Transkriptom Temelli Markör Geliştirme

RNA-Seq verilerinden elde edilen transkriptom temelli markörler, mercimek ıslahında giderek daha önemli hale gelmektedir. Bu markörlerin en büyük avantajı, doğrudan ifade edilen gen bölgelerinden türetilmiş olmalarıdır. Bu nedenle, ilgili genlerin gerçekten bir biyolojik fonksiyona sahip olduğunu gösterdikleri için fonksiyonel markör olarak kabul edilmektedir. Mercimekte yapılan de novo transkriptom montajları, 70.000–110.000 arasında unigene dizisinin ortaya çıkmasını sağlamıştır. Bu diziler kullanılarak geliştirilen EST-SSR (Expressed Sequence Tag–SSR) ve SNP markörleri, hem genetik çeşitlilik çalışmalarında hem de marker-assisted selection (MAS) uygulamalarında yaygın şekilde kullanılmaktadır (Kaur ve ark., 2014). Ayrıca Lens ervoides türünden elde edilen SSR markörlerinin %78 oranında L. culinaris genomunda da başarılı şekilde çalıştığı bildirilmektedir (Wong ve ark., 2015). Bu bulgu, yabani türlerin genetik çeşitliliği artırmak ve introgressiyon ıslahını desteklemek için önemli bir kaynak olduğunu göstermektedir. Transkriptom temelli markörler ifade edilen gen bölgelerini temsil ettiklerinden, klasik genomik markörlere kıyasla hedef karakterle daha güçlü ilişki gösterebildikleri için QTL fine-mapping çalışmalarında da avantaj sağlamaktadır. Bu da, bu markörlerin ıslah süreçlerinde daha etkin şekilde kullanılmasını sağlamaktadır (Verma ve ark., 2013; Kaur ve ark., 2011).

5. Sonuç

Son on yılda hızla gelişen genomik ve transkriptomik teknolojiler, mercimek (*Lens culinaris Medik.*) ıslahında klasik fenotipik seleksiyonun ötesine geçerek, genetik varyasyonun derinlemesine anlaşılmasını ve hedefe yönelik ıslah stratejilerinin geliştirilmesini sağlamıştır. Mercimeğin 4.0 Gbp büyüklüğündeki karmaşık genomunun çözümlenmesi, genetik bilgi birikimini sadece ıslah programlarının değil, aynı zamanda biyotik ve abiyotik stres fizyolojisinin, kalite bileşenlerinin ve adaptasyon mekanizmalarının açıklanmasında da dönüştürücü bir araç haline getirmiştir. Genomik yaklaşımlar, yüksek yoğunluklu SNP panelleri, DArTseq ve GBS tabanlı genotipleme yöntemleriyle; verim, kuraklık ve hastalık toleransı gibi kompleks karakterlerin kantitatif lokuslarının (QTL) haritalanmasına olanak tanımıştır. Bu gelişmeler sayesinde mercimek ıslahında marker assisted selection (MAS) ve genomik seleksiyon (GS) yaklaşımları, klasik yöntemlere göre daha hızlı, doğru ve ekonomik hale gelmiştir. Özellikle genomik seleksiyon, erken jenerasyonlarda (F_2–F_4) bile yüksek tahmin doğruluğu sağlayarak ıslah döngülerini önemli ölçüde kısaltmaktadır. Buna paralel olarak, transkriptomik çalışmalar da mercimeğin stres yanıt ağlarını aydınlatmada önemli rol oynamıştır. RNA-Seq analizleri, kuraklık (DREB, LEA, P5CS), tuzluluk (NHX, HKT, SOS1) ve biyotik stres (PR-protein, WRKY, TIR-NBS-LRR) gibi genlerin farklı çevresel koşullarda nasıl aktive olduğunu ortaya koymuştur. Bu bulgular, genetik direnç mekanizmalarının fonksiyonel temellerini anlamayı ve bu genlerin doğrudan ıslah hedefi olarak kullanılmasını mümkün kılmıştır. Fonksiyonel genomik ve sistem biyolojisi entegrasyonuyla birlikte,

mercimek genomunda yer alan binlerce genin yalnızca dizilimsel değil, aynı zamanda ağ düzeyinde (network-based) işlevsel bağlantıları da çözümlenmiştir. Metabolomik, proteomik ve transkriptomik verilerin bütünleştirilmesi, stres yanıtında görev alan "master regulator" genlerin belirlenmesini sağlamıştır. Ayrıca pangenom, epigenom ve tek hücreli transkriptomik (scRNA-Seq) çalışmaların yaygınlaşmasıyla, mercimek ıslahı artık yalnızca verim artırma değil, aynı zamanda iklim değişikliğine uyum, besin değeri optimizasyonu ve karbon ayak izi azaltımı gibi çok boyutlu hedeflere de hizmet eden bir bilimsel alan haline gelmiştir. Sonuç olarak; genomik, transkriptomik ve diğer "-omik" teknolojilerin bütüncül entegrasyonu, mercimek ıslahında klasik yöntemlerin sınırlarını aşarak hızlı, hedefe yönelik, veri odaklı ve sürdürülebilir yeni çeşitlerin geliştirilmesine zemin hazırlamaktadır. Bu entegrasyon, mercimeğin gelecekte iklim değişikliğine dirençli, yüksek kaliteli ve ekosistem dostu bir baklagil olarak stratejik önemini pekiştirecek; aynı zamanda Türkiye gibi genetik çeşitlilik merkezlerinde yürütülen yerli ıslah programlarına da küresel ölçekte rekabet gücü kazandıracaktır.

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MIKRODALGA ENERJISI ILE BIYOMORDANLI KUMAŞLARIN BOYANMASI VE RENK ÖZELLIKLERININ ANALIZI

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ÖZET

Günümüzde, artan sosyal farkındalık ve çevresel kaygılarla birlikte, özellikle tekstil endüstrisinde yeşil üretim ve yeşil teknolojilerin benimsenmesine yönelik bir dönüşüm başlamıştır. Doğal boyama, geçmişten günümüze toplumlar tarafından tercih edilmiştir. Tekstil boyamada sentetik boyaların kullanımı, büyük miktarda kimyasal gerektirir ve zararlı, toksik kimyasal atıklar üretir. Doğal boyamanın yeniden canlanmasıyla birlikte, tamamen doğal kaynaklar kullanılarak yapılan boyama işlemlerinin renkler üzerindeki etkileri yoğun bir araştırma konusu haline gelmiştir. Doğal boyamada, mikrodalga boyama, geleneksel boyama süreçlerinin yanında yaygın olarak kullanılmaktadır. Bu çalışmada, boyama süreçleri, biberiye (*Rosmarinus officinalis*) ile biyomordanlanmış pamuk/polyester dokuma kumaşlar üzerinde kına (*Lawsonia inermis* L.) ile gerçekleştirilmiştir. Mikrodalga boyama ve geleneksel boyama farklı sürelerde uygulanmıştır. Boyanan kumaşların renk karakterizasyonu, CIELAB renk parametreleri (L, a, b*, C*, h°) ve renk yoğunluğu (K/S) değerleri kullanılarak değerlendirilmiştir. Elde edilen verilere dayanarak, biyolojik olarak modifiye edilmiş kumaşlar ile boyanmamış kumaşlar arasındaki renk tonu, doygunluk ve renk yoğunluğu farklılıkları incelenmiştir. Ayrıca, tüm renk parametreleri ile boyama koşullarıyla ilgili değişkenlerin dağılımı arasındaki ilişkiyi belirlemek için Temel Bileşen Analizi (PCA) uygulanmıştır. Bu çalışma, geleneksel doğal boyama işlemlerine kıyasla mikrodalga destekli doğal boyamanın, sürdürülebilir yeşil tekstil üretiminde daha hızlı, daha ekolojik ve yüksek verimli bir alternatif olabileceğini göstermektedir.

Anahtar Kelimeler: Doğal Boyama, Mikrodalga, *Lawsonia inermis* L., biyomordan

DYEING OF BIOMORDANTED FABRICS WITH MICROWAVE ENERGY AND ANALYSIS OF COLOR PROPERTIES

ABSTRACT

Today, with increasing social awareness and environmental concerns, a transformation has begun, particularly in the textile industry, towards the adoption of green production and green technologies. Natural dyeing has been preferred by societies from the past to the present. The use of synthetic dyes in textile dyeing requires large amounts of chemicals and produces harmful, toxic chemical waste. With the revival of natural dyeing, the effects of dyeing processes using entirely natural resources on colors have become a subject of intense research. In natural dyeing, microwave energy dyeing is widely used alongside traditional dyeing processes. In this study, dyeing processes were performed with henna (*Lawsonia inermis* L.) on cotton/polyester woven fabrics biomordanted with rosemary (*Rosmarinus officinalis*). Microwave dyeing and traditional dyeing were applied for different durations. The color characterization of the dyed fabrics was evaluated using CIELAB color parameters (L, a, b*, C*, h°) and color intensity (K/S) values. Based on the data obtained, the differences in hue, saturation, and color intensity between the bio-modified fabrics and the undyed fabrics were examined. Furthermore, Principal Component Analysis (PCA) was applied to determine the relationship between all color parameters and the distribution of variables related to dyeing conditions. This study demonstrates that microwave-assisted natural dyeing, compared to traditional natural dyeing processes, could be a faster, more ecological, and highly efficient alternative in sustainable green textile production.

Keywords: Natural Dyeing, Microwave, *Lawsonia inermis* L., biomordant

1.INTRODUCTION

Natural dyeing is an ancient art that has been practised since prehistoric times. With the discovery of synthetic dyes in 1856, natural dyes declined in use (Ado et al., 2014). Synthetic dyes have been adopted as alternatives to natural dyes in many fields due to their wide colour range, ease of application, and availability. In recent years, growing environmental awareness and concerns about sustainability have renewed interest in natural dyes, particularly in the textile industry. Mordants are used to improve the binding of natural dyes, which are obtained from plant parts such as roots, stems, and leaves, to fabrics. Metal salts are among the most widely used mordants in the dyeing industry. However, there are concerns about the environmental impact of metal salts. As a result, biomordants have begun to be used as more environmentally friendly alternatives. Common biomordants include botanical sources such as pomegranate peel, acacia, tannic acid, myrobalan, turmeric, oak, henna, lemon, tamarind, rosemary, and aloe vera (Cuce et al., 2022; Korkmaz et al., 2023, Benli, 2024; Kılınç et al., 2025). The natural dyeing process is generally carried out using conventional methods. However, in recent years, microwave energy dyeing has become popular due to its speed, effectiveness, and high energy efficiency. The literature reports that highly efficient results have been achieved in dyeing studies using microwaves (Yavaş et al., 2017). Rosemary (*Rosmarinus officinalis*) is a common houseplant cultivated in many regions worldwide, particularly in the Mediterranean. Rosemary can serve as an alternative to metal mordants due to its high phenolic content (İşmal et al., 2014). *Lawsonia inermis* (Henna) contains secondary metabolites such as alkaloids, flavonoids, coumarins, and tannins. Its main component is reported to be lawsone (2-hydroxy-1,4-naphthoquinone) (Supian and Osman, 2023). According to the literature, lawsone obtained from *Lawsonia inermis* can be used as a natural and environmentally friendly red-orange dye. *L. inermis* demonstrates good dyeing efficiency on protein fibers, but provides low and limited dyeing efficiency on cellulosic fibers; however, successful dyeing can be achieved at high temperatures on polyester. Due to its sustainable nature, it has been reported as a long-term environmentally friendly and ecological alternative for the textile industry (Bhuiyan et al., 2017). In this study, conventional methods and microwave energy were used to dye cotton/polyester blended fabrics. Both the mordanting and dyeing processes were carried out for different durations. Rosemary (*Rosmarinus officinalis*) was used as the biomordant and henna (*Lawsonia inermis*) as the dye. The colour properties of the dyed fabrics were evaluated using CIELAB (L, a, b*, C*, h°) colour parameters and colour intensity (K/S) values. The relationship between the colour parameters was interpreted using principal component analysis (PCA).

2. MATERIAL AND METHOD

2.1 Material

Cotton/polyester (75/25) fabric was used in the dyeing and mordanting processes. Fabric properties are given in Table 1.

Table 1. Fabric Properties

Properties	Cotton/Polyester(75/25%)
Fabric construction	Plain weave 1/1
GSM (g/m^2)	110
Ends per inch (cm^{-1})	24
Picks per inch (cm^{-1})	16
Warp count (Nm)	30
Weft count (Nm)	60

2.2 Mordanting Process

Pre-mordanting was applied in the study. A 10% rosemary (*Rosmarinus officinalis*) solution was used for the mordanting process. The mordanting was carried out using the traditional method at boiling temperature for 1 hour, and with microwave energy for 3 minutes and 5 minutes.

2.3 Dyeing Process

Dye concentrations were calculated based on fabric weight, with a 40% henna (Lawsonia inermis) concentration used during the dyeing process. The fabric was subjected to microwave dyeing at 800 watts using pure water at a 1:50 flotte ratio for 1, 3, and 5 minutes. Additionally, all fabrics underwent a 30-minute conventional dyeing process. After dyeing, the fabrics were washed in cold water, then in hot (boiling point) water, and finally in cold water again to remove any unbound dyes. The dyed fabrics were then left to dry.

2.4 Color Measurement

After the mordanting and dyeing processes were completed, colour measurements were performed using an LS175 colorimeter. Measurements were conducted under a D65 light source and 10° standard observer conditions. Reflectance (R) values were obtained in the visible range (400–700 nm) and converted to colour intensity (K/S) values using the Kubelka–Munk equation (Equation 1).

$$K/S = (1 - R)^2 / 2R \quad (1)$$

In addition to colour intensity measurements, the CIELAB colour coordinates of the samples were also determined. L* (lightness: 0 = black, 100 = white), a* (positive = red, negative = green), and b* (positive = yellow, negative = blue) values were measured; the C* (chroma, 0 = dull, 100 = vivid) parameter was also used to evaluate colour saturation.

3.RESULTS

The color measurement values of dyed cotton-polyester fabrics are given in Table 2.

Table 2. Color values of dyed fabric

Samples	L*	a*	b*	C*	h°	λ	K/S
ST	82.98	2.40	12.05	12.28	78.6	400	0.43
R1N1ML	75.97	2.58	15.14	15.35	80.3	400	0,92
R1N3ML	75.78	1.84	14.31	14.42	82.6	400	0,90
R1N5ML	75.19	1.88	14.49	14.61	82.6	400	0,93
R1N30NL	64.62	0.87	15.58	15.60	86.8	400	2,18
R3M1ML	75.84	2.43	14.27	14.47	80.3	400	0,88
R3M3ML	73.80	1.88	14.71	14.82	82.7	400	1,07
R3M5ML	67.61	2.23	16.33	16.48	82.2	400	1,65
R3M30NL	63.27	1.33	16.03	16.08	85.2	400	2,26
R5M1ML	75.38	2.61	14.52	14.75	79.8	400	0,92
R5M3ML	74.40	2.30	14.32	14.50	80.8	400	1,04
R5M5ML	72.71	2.11	14.87	15.00	81.9	400	1,48
R5M30NL	67.68	1.61	15.53	15.61	84.0	400	1,72
1ML	75.94	4.32	14.34	14.97	73.1	400	0,81
3ML	75.45	3.33	13.75	14.15	76.3	400	0,87
5ML	71.45	2.61	14.80	15.02	79.9	400	1,28
30NL	66.16	1.16	14.91	14.95	85.5	400	1,81

R ➔ 1st Position: Mordant Material, **1** ➔ 2nd Position: Mordanting Time **N** ➔ 3rd Position: Mordanting Type **30** ➔ 4th Position: Dyeing Time **NL** ➔ 5th Position: Dyeing Type

L * Lightness (0 = black, 100 = white), ; **a*** ± Red/green, ; **b*** ± Yellow/blue, **C *** To vividness-dullness (100 = vivid, 0 = dull),**R**: *Rosmarinus officinalis* **,** *M:Microwave, N; Normal,* ***L;*** *L. inermis*

Colour parameters are important concepts used to determine the similarities and differences between dyed samples. When samples are examined in terms of L* value, it is observed that brightness decreases after the dyeing process. The sample with code R3M30NL, which was mordanted with microwave energy and dyed traditionally, has the lowest lightness value. Traditionally dyed samples are less bright than those dyed with microwaves. The a* value, used to define red and green colour tones, is lower in traditionally dyed samples compared to the standard sample, while it is higher in samples dyed only with microwave energy. Other samples have a* values close to the standard fabric. The sample with code 1ML has the highest value, while the sample R1N30NL has the lowest. In terms of the b* value, used to determine yellowness and blueness, all samples are more yellow than the standard sample. The R3M5ML sample has the highest yellow hue. For vividness (C*) values, all samples are more vivid than the raw fabric. The R3M5ML sample has the highest chroma value. Regarding hue values, all samples have similar values. According to Figure 1, the samples are in the orange-yellow region. For colour fastness (K/S) values, there has been an increase in all samples compared to the raw fabric. Samples dyed using natural methods have a higher colour fastness value.

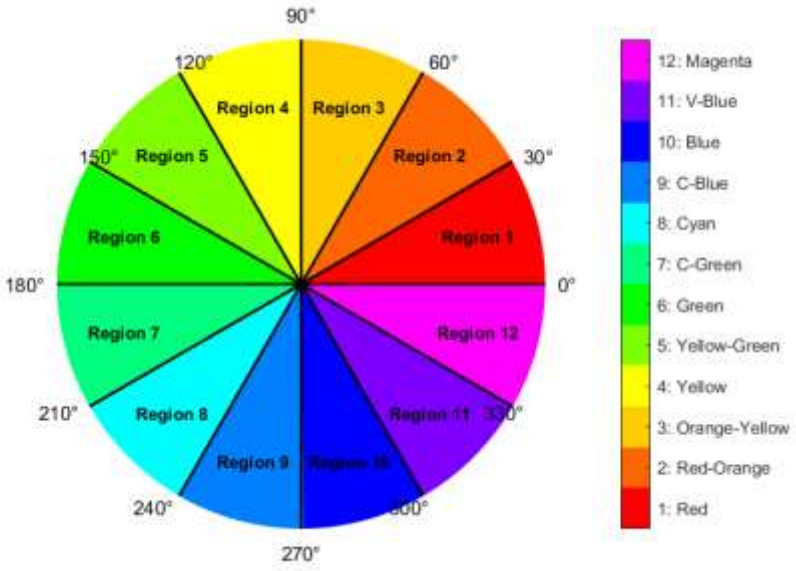

Figure 1. Color Wheel

Eigenvalue graphics are shown in Figure 2. The eigenvalue graph indicates that PC1 and PC2 have values greater than 1. PC1 (eigenvalue 5.7) is the most dominant component and is meaningful for explaining the data, along with PC2 (eigenvalue 2.2). Therefore, the data can be examined on a two-dimensional map. The proportion of variance explained by these two components is 77.56%, as shown in Figure 3.

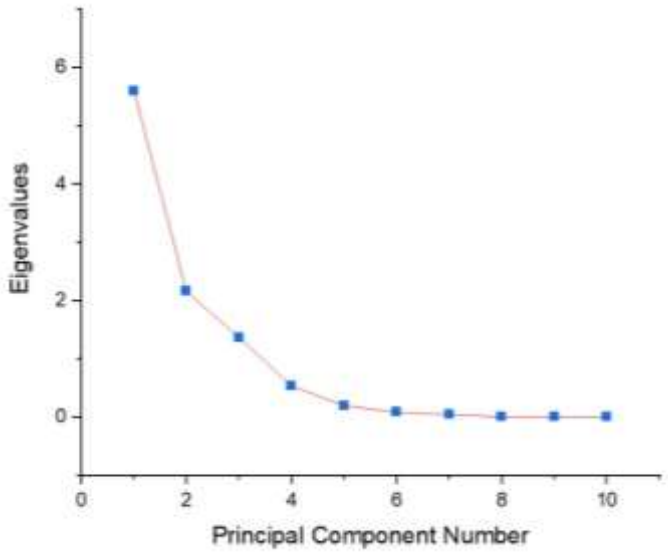

Figure 2. Eigenvalues graph

The principal component analysis graph is presented in Figure 3. According to this graph, there is a negative correlation between L* and K/S values. A positive correlation exists among b*, C*, MT (mordant type), and MAT (mordant application time) values. Another group showing positive correlation includes the K/S, h, and DAT (dye application time) variables. The standard control sample is distant from all other samples, particularly those coded R. The normally dyed samples coded NL are located in the lower right corner, while the microwave-dyed samples coded ML are clustered together. Additionally, the mordanted samples are positioned separately from the non-mordanted ones.

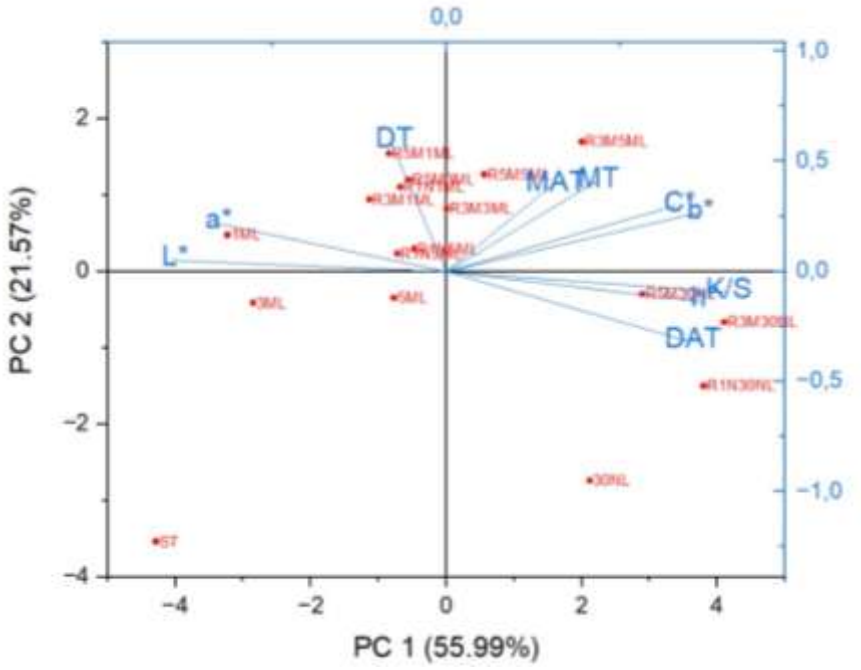

Figure 3. Principal Component Analysis (PCA) Biplot

4. CONCLUSION

The findings of this study show that long-term, optimised natural dyeing processes using effective natural dyeing materials, particularly henna (*Lawsonia inermis*) and rosemary (*Rosmarinus officinalis*), can achieve colour intensity comparable to that of synthetic dyes. The use of microwave energy in natural dyeing systems is recognised as an environmentally friendly, energy-efficient method with shorter processing times, achieving deep and effective colours comparable to traditional dyeing, provided the appropriate materials, mordant, and processing time are selected. This offers a strong alternative for the textile industry to achieve its environmental goals.

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DESIGN AND MODELING OF NEXT-GENERATION GRINDING AIDS AND INVESTIGATION OF THEIR EFFECTS

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ABSTRACT

Improving energy efficiency in industrial grinding processes requires the development and comprehensive evaluation of next-generation grinding aids with tailored physicochemical characteristics. In this context, the rational design, molecular modeling, and mechanistic examination of novel additives provide critical insights that guide experimental studies. By theoretically screening candidate molecules prior to laboratory work, it becomes possible to identify structures with high performance potential, thereby reducing experimental workload, cost, and time loss. Within the scope of this study, five different ester-based grinding aid molecules were modeled in detail. The molecular structures were optimized using the Gaussian 09 software package with the DFT/B3LYP method and the 6-31G(d,p) basis set. Additionally, adsorption geometries of these molecules with Ca^{2+} ions were investigated to elucidate their interaction mechanisms on cement particle surfaces. Adsorption energies were calculated, and Mulliken charge distributions, HOMO–LUMO energy gaps, and electron density maps were analyzed to characterize the electronic features governing surface affinity and reactivity. The integrated evaluation of these parameters allowed the identification of the most promising candidate molecule with superior theoretical performance. This multiscale and computationally driven approach offers an innovative framework for the development of sustainable, high-efficiency grinding technologies and provides a scientific basis for the next generation of energy-saving additives.

Keywords: Grinding aid, DFT, calcium adsorption, energy efficiency, surface interaction

Introduction

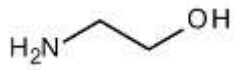
Energy consumption in cement and mineral processing industries remains a critical challenge, with grinding operations accounting for a substantial portion of total energy demand (Chehreh Chelgani et al., 2025). Conventional grinding aids have been widely employed to enhance comminution efficiency; however, their performance is often limited by non-specific physicochemical properties and insufficient mechanistic understanding (International Cement Review, 2025). As global sustainability goals increasingly emphasize energy reduction and resource optimization, the development of next-generation additives with tailored molecular characteristics has become an urgent priority (Kobya et al., 2025; Çinku et al., 2025).

Recent advances in computational chemistry and molecular modeling provide powerful tools to rationally design and evaluate candidate molecules prior to experimental validation. Density Functional Theory (DFT) calculations enable the prediction of adsorption behavior, electronic structure, and reactivity patterns, thereby offering insights into the fundamental interactions between grinding aids and cement particle surfaces. Such theoretical screening not only reduces experimental workload and costs but also accelerates the identification of high-performance additives with superior energy-saving potential.

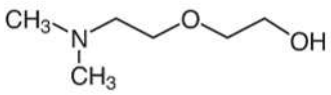
In this study, a systematic computational investigation was conducted on five ester-based grinding aid molecules. Their molecular geometries were optimized using the Gaussian 09 software package with the DFT/B3LYP method and the 6-31G(d,p) basis set (Gaussian Inc., 2025). Adsorption interactions with Ca^{2+} ions were examined to elucidate binding mechanisms, while adsorption energies, Mulliken charge distributions, HOMO–LUMO energy gaps, and electron density maps were analyzed to characterize electronic features governing surface affinity. The integrated evaluation of these parameters enabled the identification of the most promising candidate molecules, thereby establishing a computationally driven framework for the rational design of sustainable, high efficiency grinding technologies.

Materials and Methods

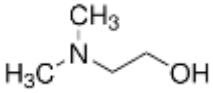
Ester molecules are readily obtained from the acid-catalyzed reaction of carboxylic acids with alcohols. In this study, the structures of the modified esters obtained from the reaction of acetic acid with the amino alcohol molecules shown in Figure 1 were proposed, and their adsorption with Ca2+ ions was investigated. Optimization and frequency calculations of the molecules were performed in the gas phase using the DFT/B3LYP method and the 6-31G(d,p) basis set [6]. All calculations were performed using the Gaussian 09 program [7].



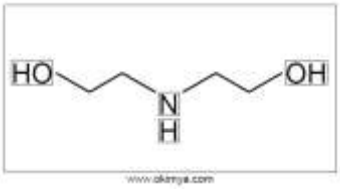
Ethanoleamine



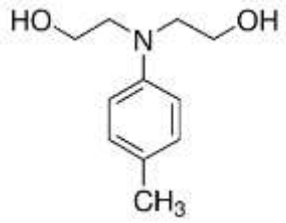
2-[2-(Dimethylamino)ethoxi]ethanole



2-Dimethylaminoethanol



Diethanol amine



2,2′-(4-Methylphenylimino)diethanol

Figure 1. Ethanolamines used in ester synthesis

Results and Discussions

Molecular structures optimized and frequency calculated using the DFT/B3LYP method and the 6-31G(d,p) basis set, showing no negative frequencies, are depicted in Figure 1.

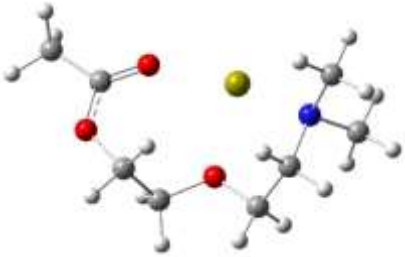
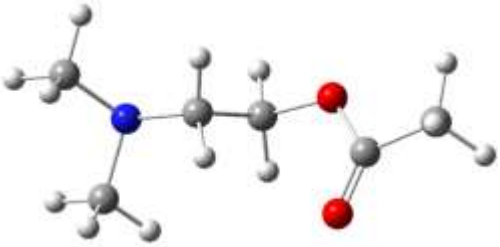
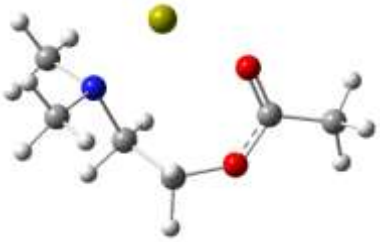
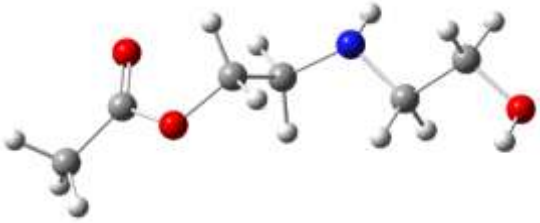
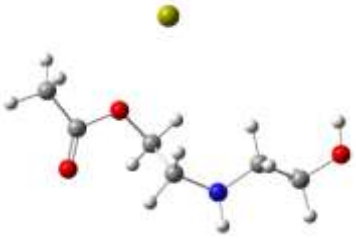
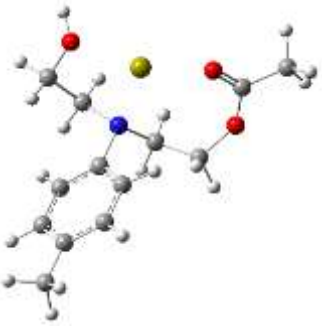
	
Ester1	Ester1-Ca
	
Ester2	Ester2-Ca
	
Ester3	Ester3-Ca
	
Ester4	Ester4-Ca
	
Ester5	Ester5-Ca

Figure 1. Optimized molecular structures of molecules adsorbed with ester 1, 2, 3, 4 and 5 molecules and Ca+2 ions

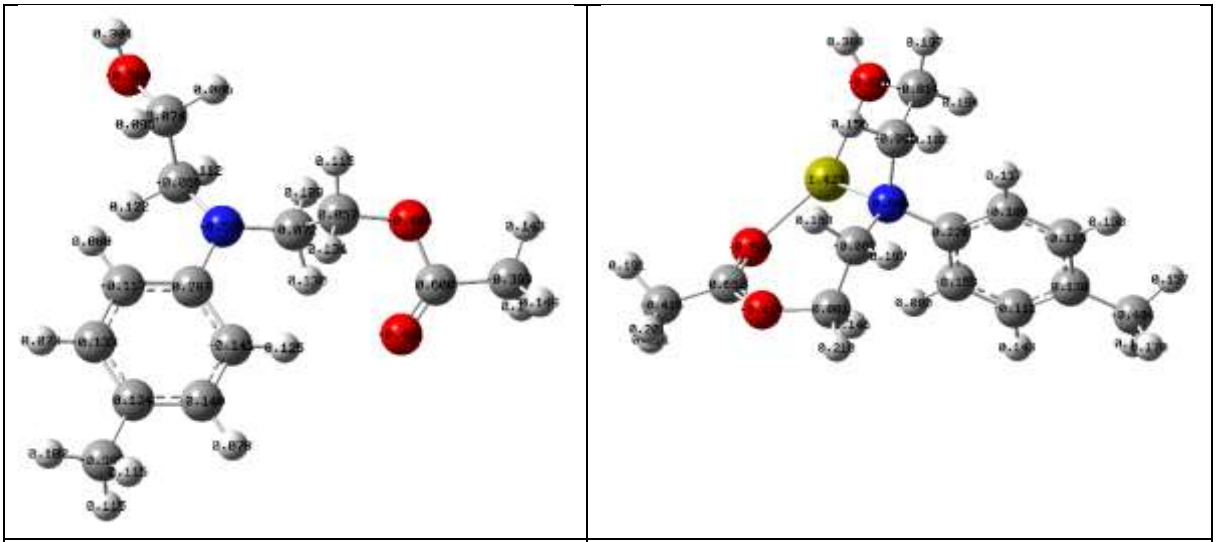
The energies and adsorption energies of the modeled ester molecules and the molecules obtained as a result of their adsorption with Ca+2 ions obtained using the DFT/B3LYP method and the 6-31G(d,p) basis set are listed in Table 1.

Table 1. Adsorption energies of ester molecules calculated in the B3LYP/6-31G(d,p) method and basis set

Molecules	**Energy (a.u.)**	**Adsorption energy (eV)**
Ester1	-363.057272	-5.14
Ester1-Ca	-1040.113941	
Ester2	-595.504294	-6.78
Ester2-Ca	-1272.620442	
Ester3	-441.673996	-5.10
Ester3-Ca	-1118.728213	
Ester4	-516.988200	-5.21
Ester4-Ca	-1194.046418	
Ester5	-787.260127	-6.88
Ester5-Ca	-1464.380020	

Table 1 shows that among the ester molecules, the molecule with the highest adsorption energy with the Ca+2 ion is Ester5. The adsorption energy for this molecule was calculated as -6.88 eV. Ester2 follows with -6.78 eV. The molecule with the lowest adsorption energy is Ester1, formed by acetic acid and ethanol amine. Based on these results, Ester5 is expected to have the best grinding facilitating properties.

The pre- and post-adsorption mulliken loads of the ester5 molecule, which gave the best adsorption result, are given in Figure 2.

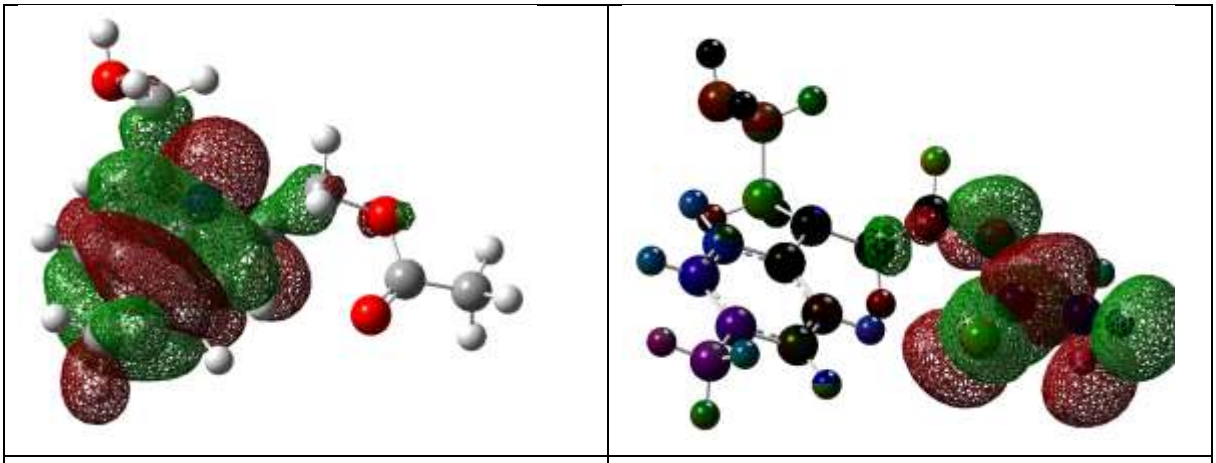


Ester5 | Ester5-Ca

Figure 2. Mulliken charges of the ester5 molecule before and after adsorption

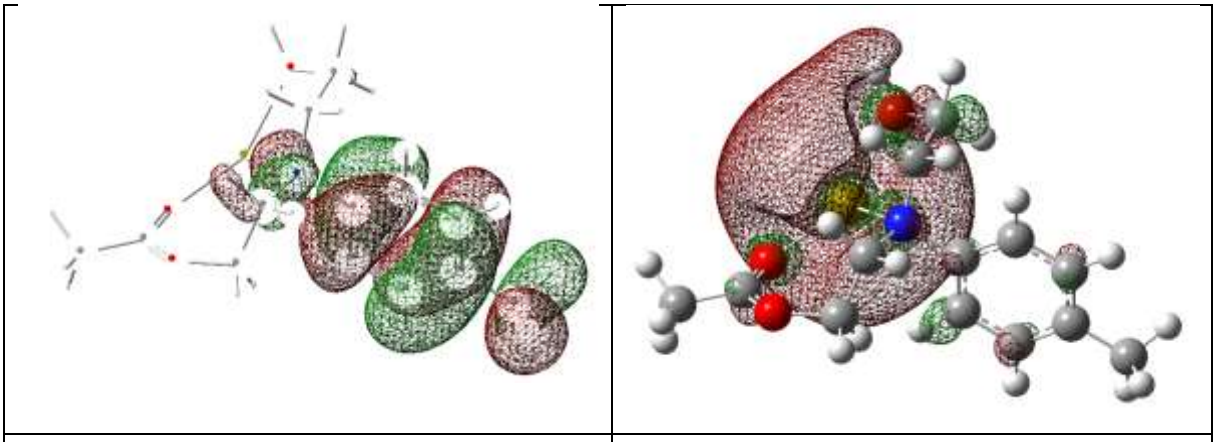
The mulliken charges of the heteroatoms, three oxygen atoms, and one nitrogen atom of the ester5 molecule were calculated as -0.560, -0.486, -0.451, and -0.528, respectively. The oxygen atoms of the same molecule that adsorbed with Ca2+ ions increased to -0.626 and -0.598, respectively, while the charge of the other oxygen atom decreased to -0.417. The nitrogen atom that participated in adsorption increased to -0.693. The charge of the calcium ion was calculated as 1.423.

The HOMO and LUMO orbitals of the molecules on which ester5 and Ca+2 ion are adsorbed are depicted in Figures 3 and 4.



Ester5-HOMO	Ester5-LUMO

Figure 3. HOMO and LUMO orbitals of the ester5 molecule



Eser5-Ca-HOMO	Ester5-Ca-LUMO

Figure 4. HOMO and LUMO orbitals of the ester5-Ca molecule

The HOMO molecular orbitals of the ester5 and ester5-Ca molecules are similar, but have phenyl pi character. The LUMO orbital of the ester5 molecule is concentrated on the carbonyl pi electrons, while that of the ester5-Ca molecule is concentrated on the calcium ion.

Conclusions

The calculations indicate that ester 5 has the strongest adsorption energy and is the most suitable candidate for milling facilitating properties. Mulliken charges and HOMO–LUMO analyses explain the binding mechanism of the Ca^{2+} ion through both electronic redistribution and orbital interactions. These findings are believed to provide guidance for the design of metal–organic complexes, catalyst development, and materials chemistry applications.

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EXPERIMENTAL AND THEORETICAL INVESTIGATION OF THE FTIR AND NMR SPECTRA OF THE ESTER MOLECULE OBTAINED FROM THE SYNTHESIS OF ACETIC ACID AND TIPA

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ABSTRACT

Esterification reactions typically occur through the condensation of an acid and an alcohol under appropriate catalytic conditions, forming structurally diverse and industrially relevant ester derivatives. In this study, a novel ester molecule synthesized via the esterification of tris(isopropanol)amine (TIPA) with acetic acid was subjected to comprehensive structural characterization using both experimental spectroscopy and theoretical modeling. Fourier Transform Infrared Spectroscopy (FTIR) and Nuclear Magnetic Resonance (NMR) spectroscopy were employed to experimentally verify the molecular structure, while Density Functional Theory (DFT)-based calculations were used to simulate the vibrational and electronic environments of the molecule. The theoretical analysis involved full geometry optimization at the B3LYP/6-31G(d,p) level, followed by simulation of FTIR vibrational modes using Gaussian 09 and GaussView software. All fundamental vibrational modes were assigned, and the theoretical C=O and C–O stretching frequencies exhibited strong agreement with the experimental values, with deviations remaining below 20 cm^{-1}. Furthermore, NMR chemical shifts were calculated using the Gauge-Including Atomic Orbital (GIAO) method. The chemical shift values of key nuclei, particularly the carbonyl carbon and the protons in the vicinity of the hydroxyl and isopropyl groups, showed excellent correlation with the experimental spectra ($R^2 > 0.98$). A comparative evaluation of experimental and computational FTIR and NMR spectra confirmed the successful formation of the ester bond and provided insights into the conformational behavior of the isopropyl groups within the molecular framework. The integration of DFT calculations with spectroscopic techniques demonstrated the strength of this combined methodology for molecular-level structural verification and functional group identification. Overall, the ester molecule synthesized from acetic acid and TIPA was successfully characterized using a dual experimental–theoretical approach, and the high level of agreement between the two datasets confirms both the structural integrity and the synthetic success of the target molecule. This study highlights the value of DFT-supported spectroscopic analysis as a robust methodology for the design and characterization of new ester derivatives.

Keywords: TIPA, esterification, FTIR, NMR, DFT, spectral analysis, molecular modeling

Introduction

Esterification reactions are among the most fundamental transformations in organic chemistry and have a wide range of applications in both academic and industrial applications. Esters are considered critical functional compounds in many areas, from polymer production and drug synthesis to surfactants and coating technologies. Therefore, the synthesis and structural verification of new ester derivatives is an important research topic that requires understanding at the molecular level [1].

Trisisopropanolamine (TIPA), a highly reactive alcohol derivative due to its multifunctional hydroxyl groups, is widely used in surfactants and additive systems. The esterification reaction between TIPA and acetic acid has been studied only limitedly in the literature, and detailed elucidation of the structural properties of new ester derivatives obtained from this system is of scientific importance [2,3].

In the structural characterization of molecules, Fourier Transform Infrared Spectroscopy (FTIR) and Nuclear Magnetic Resonance (NMR) techniques stand out as powerful tools for the determination of functional groups and the verification of bond structures. However, supporting experimental data with theoretical calculations based on Density Functional Theory (DFT) allows for more comprehensive interpretation of spectral data and reliable confirmation of molecular geometry [1]. This study focuses on the characterization of a new ester derivative synthesized from TIPA and acetic acid using both experimental and theoretical methods. Comparison of FTIR and NMR data with DFT calculations reveals the structural integrity of the molecule and contributes to the understanding of the esterification mechanism and the conformational effects of isopropyl groups. Thus, a robust methodological approach is presented for the design and characterization of new ester derivatives.Kaynaklar

Materials and Methods

TIPA, acetic acid, and catalyst were added to a 250 ml, two-necked glass flask at a 1:1 molar ratio, and the reaction was carried out using the esterification polymerization method at 90°C for 3 hours. The product yielded 40%.

The resulting M-TIPA molecule was characterized using FTIR, NMR, and GC-MS techniques.

The resulting M-TIPA molecule was optimized using the Gaussian 09 program, the DFT/B3LYP method, and the 6-31G(d,p) basis set. Frequency calculations for the optimized molecule confirmed that it was optimized in the most probable geometry.

The optimized molecular structure of the molecule is depicted in Figure 1.

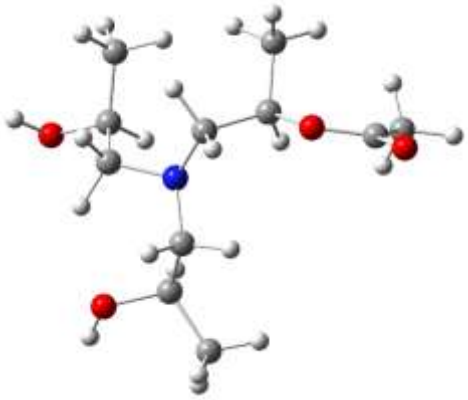

Figure 1. Optimized molecular structure of the M-TIPA molecule

Results and Discussion

Synthesis

The FTIR spectrum of the M-TIPA molecule, obtained from the reaction of one mole each of acetic acid and TIPA in the presence of a catalyst, is shown in Figure 2. The carbonyl stretching vibration of acetic acid, observed around 1750 cm-1, shifted to a weaker field in the M-TIPA molecule and decreased in intensity. The broad band observed in the TIPA molecule between 3000 and 3500 cm-1 is also observed in the M-TIPA molecule, providing strong evidence that synthesis has occurred.

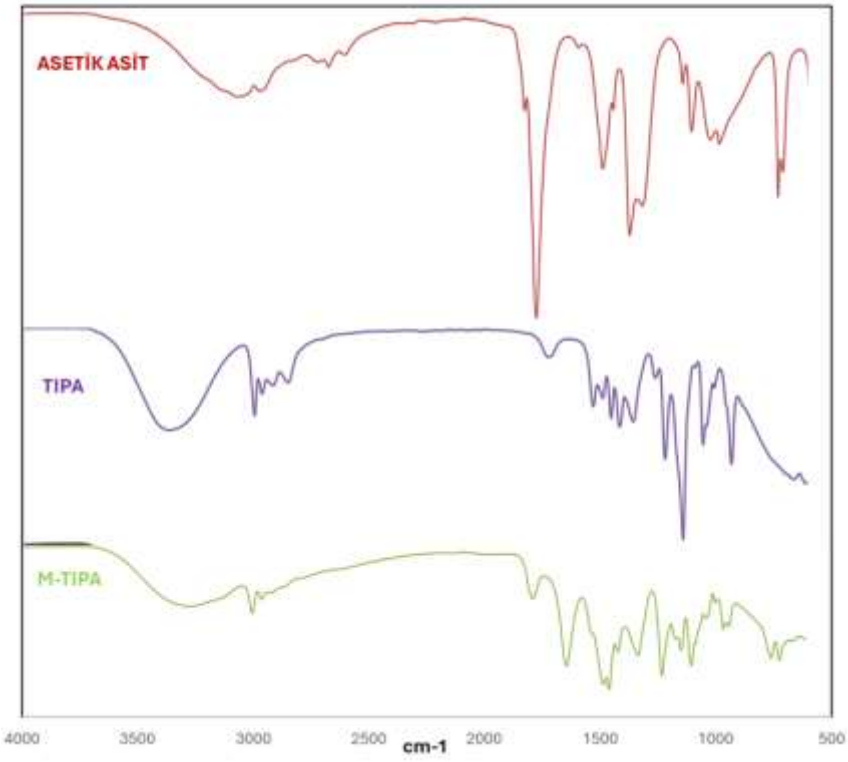

Figure 2. FT-IR spectra of acetic acid, TIPA and M-TIPA molecules

GC-MS chromatograms of the obtained M-TIPA and TIPA molecules are given in Figure 3.

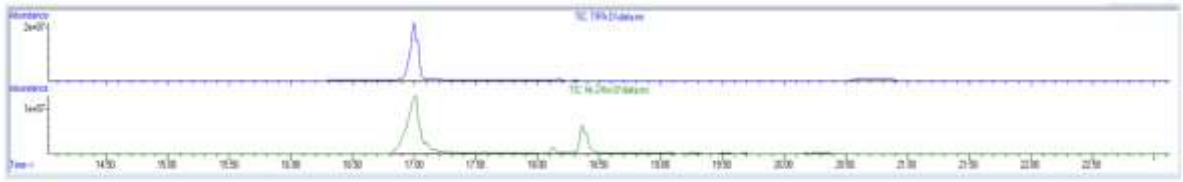

Figure 3. GC-MS chromatograms of M-TIPA and TIPA molecules

The peak for the TIPA molecule was observed at minute 17. When the chromatogram of the M-TIPA molecule was examined, in addition to the peak at minute 17, a peak belonging to a molecule with a higher molecular weight than TIPA was also observed at minutes 18 and 40. This result supports the synthesis of the M-TIPA molecule.

Finally, the 13C NMR spectrum of the M-TIPA molecule was obtained. The obtained spectrum is depicted in Figure 4.

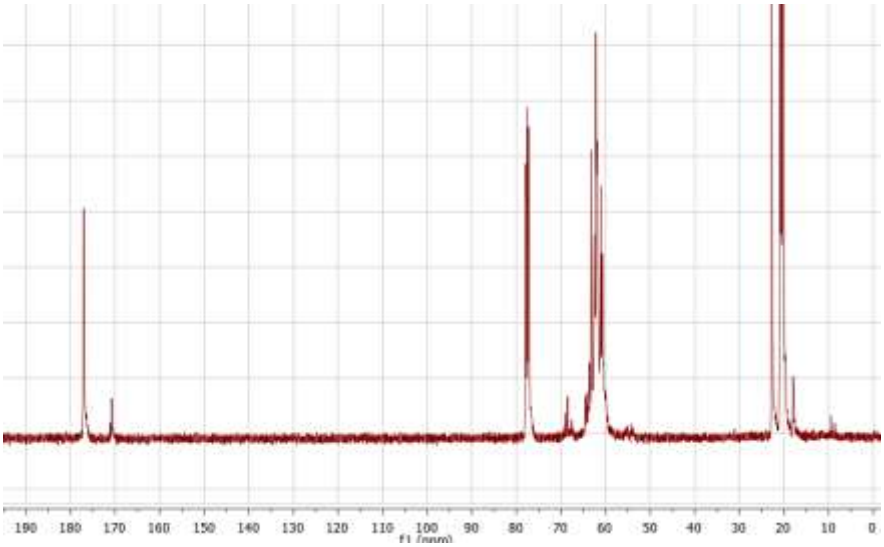

Figure 4. 13C NMR spectrum of the M-TIPA molecule

When Figure 4 is examined, the observation of a peak in the 170-180 ppm range, in addition to the peak belonging to the carbonyl carbon of acetic acid, indicates that the M-TIPA molecule has been synthesized. All these results indicate that the M-TIPA molecule was synthesized with approximately 50% yield.

FTIR spectrum

The synthesis and characterization of the M-TIPA molecule was optimized and its frequency calculation was performed using the DFT/B3LYP method and the 6-31G(d,p) basis set. Because the obtained frequency values were higher than expected, a scale factor was used. A scale factor of 0.98 was used for the 400-1800 cm-1 range and 0.96 for the 1800-4000 cm-1 range. The experimental and theoretical spectra obtained are compared in Figure 5.

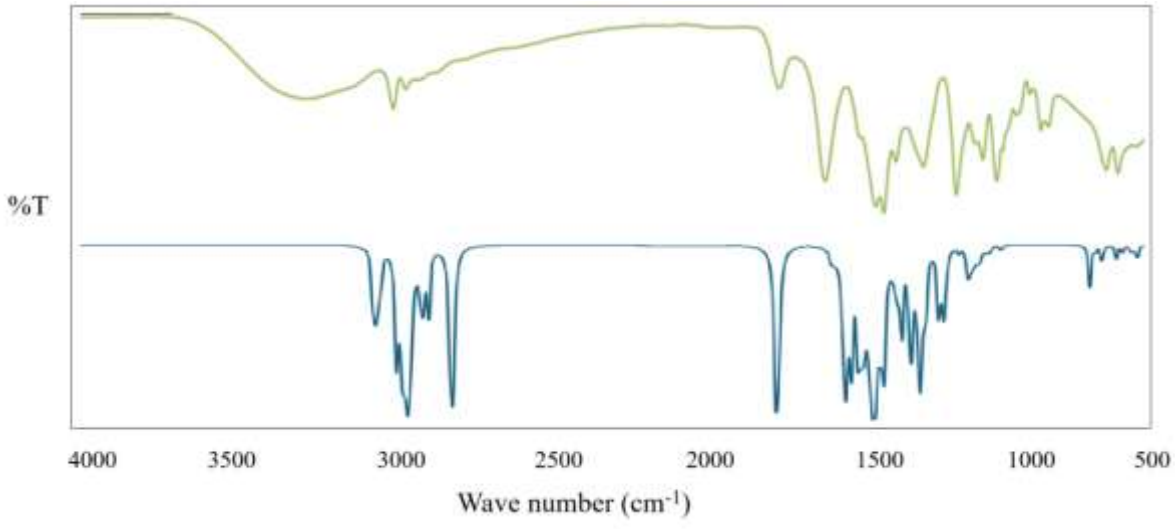

Figure 5. Comparison of experimental (green) and theoretical (blue) FTIR spectra of the M-TIPA molecule

Some experimentally and theoretically calculated vibration modes of the M-TIPA molecule are listed in Table 1.

Table 1. Some selected experimental and theoretical vibrational modes of the M-TIPA molecule

25	480	10,3244	511	C-C bending
33	644	32,8783		
37	1027	13,8717	1018	C-H bending
38	1040	21,0325	1022	C-H bending
39	1052	13,2353		
41	1065	17,3949	1083	C-C bending
45	1146	80,928		
46	1163	50,9761	1144	C-H bending
47	1168	44,2188		
48	1215	127,2637		
49	1232	210,4609	1208	C-H bending
50	1240	31,8817		
52	1260	129,2107		
53	1270	35,2958		
54	1291	79,7708		
55	1304	36,3159		
56	1314	23,5333		
57	1327	15,941		
59	1354	16,3285		
60	1355	138,2075	1322	C-H bending
62	1366	84,6889		
63	1382	315,044		
64	1387	70,5536		
66	1397	112,6082		
68	1398	159,2753		
70	1402	20,8374		
71	1404	38,8999		
72	1412	52,4198		
73	1419	19,3163		
74	1422	23,3166		
75	1430	164,2205		
77	1444	175,9532		
79	1469	154,125	1453	C-H bending
80	1482	21,4137		
81	1485	176,2765	1483	C-H bending
82	1491	151,7227		
84	1501	24,6949		
87	1534	17,9458	1544	O-H bending, C-H bending
88	1777	507,0861	1763	C=O stretching
89	2721	176,5407		
90	2726	230,409		
91	2802	84,527		
92	2806	2,0128		
93	2821	53,0838		
94	2832	42,5961		
97	2861	63,5406		
98	2867	226,783		
99	2871	117,2917	2875	C-H stretching
100	2876	41,8758		
101	2878	97,8409		
102	2886	65,2689		
103	2888	73,5728		
104	2890	47,6186		
105	2902	73,7497	2900	C-H stretching
106	2907	31,6911		
107	2908	75,9456		
108	2963	64,3465	2955	C-H stretching
109	2975	63,1444	2973	C-H stretching
111	2987	41,4869		
R2	0,9996			

The carbonyl stretching vibration of the M-TIPA molecule, observed at 1777 cm-1, was theoretically calculated at 1763 cm-1. The C-H aliphatic stretching vibrations were observed below 3000 cm-1, as expected, and the experimental and theoretical values are in good

agreement. When all experimental and theoretical values were compared, an R2 value of 0.9996 was calculated. All other vibrational modes are listed in Table 1.

NMR Spectrum

A comparison of the experimental and theoretical 13C-NMR spectra is shown in Figure 6.

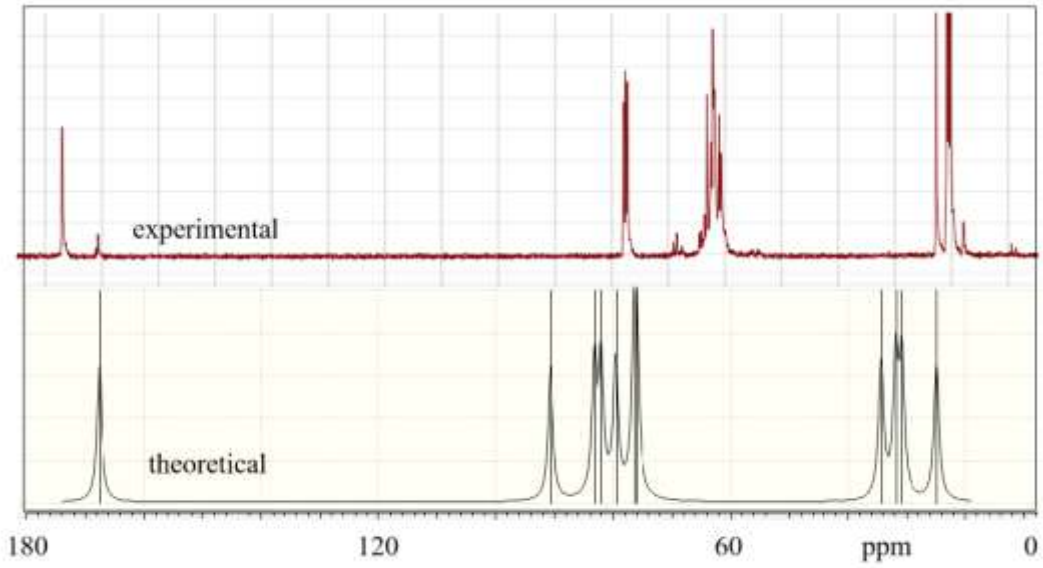

Figure 6. Experimental and theoretical 13C-NMR spectrum of the M-TIPA molecule

An examination of Figure 6 reveals that the experimental and theoretical spectra are in good agreement. The peak belonging to the carbonyl carbon atom, observed experimentally at 170.0 ppm, was theoretically calculated at 170.3 ppm. Carbon atoms belonging to the aliphatic CH3 and CH2 groups, observed at 20-23 ppm and 60-79 ppm, were calculated at 21-30 ppm and 69-91 ppm, respectively.

Conclusions

In this study, a new ester derivative synthesized from the esterification reaction between tris(isopropanol)amine (TIPA) and acetic acid was successfully characterized using a combined experimental and theoretical approach. FTIR, NMR, and GC-MS analyses confirmed the structural transformation resulting from the formation of the ester bond. The shift of the carbonyl stretching vibration to lower wavenumbers and the presence of characteristic peaks validating the C–O and C=O functional groups demonstrated the successful conversion of the reactants to the target ester product.

The GC-MS chromatogram revealed new peaks at higher retention times compared to pure TIPA, indicating an increase in molecular weight and supporting the structural modification. Additionally, the ^13C-NMR spectrum exhibited a distinct resonance near 170–180 ppm corresponding to the carbonyl carbon of the ester, which further validated the final molecular structure.

Complementary Density Functional Theory (DFT) calculations performed at the B3LYP/6-31G(d,p) level provided optimized molecular geometry and vibrational frequency predictions consistent with the experimental findings. After appropriate scaling, the correlation between experimental and theoretical FTIR wavenumbers yielded a high determination coefficient ($R^2 \approx 0.9996$), demonstrating excellent agreement between spectroscopic observations and computational modeling. Similarly, the theoretical NMR chemical shift predictions closely

matched the experimental spectra, particularly for the carbonyl and aliphatic regions, confirming the reliability of the structural assignment.

Overall, the consistency of the experimental data with the theoretical predictions confirms the successful synthesis and structural integrity of the M-TIPA ester molecule. The findings highlight the effectiveness of integrating quantum chemical modeling with spectroscopic methods to support molecular structure elucidation. Future work may explore the functional properties, reaction kinetics, and potential industrial applications of the synthesized ester derivative, particularly in chemical additive and polymer industries where multifunctional organic molecules such as TIPA-based esters are widely utilized.

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EFFECT OF FILLERS REINFORCED INTO THE POLYAMIDE-6 MATRIX ON THERMAL CONDUCTIVITY

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ABSTRACT

Polymer matrix composites are widely used in many industries such as automotive, electronics, and aviation due to their light weight, chemical resistance, ease of shaping, and ease of manufacturing. One of the most important properties that determine the performance of these materials is thermal conductivity. While rapid removal of heat is required in some systems, in other systems reducing heat transfer is of great importance in terms of safety, energy efficiency, and product stability. Depending on the application requirements, increasing or decreasing the thermal conductivity values of polymers has become a critical engineering approach. High thermal conductivity provides an advantage for electronic chips, engine cooling systems or thermal interface materials; whereas low thermal conductivity is preferred in applications such as refrigerator insulation, building insulation elements, avionic systems, and ammunition boxes by limiting heat transfer for safety and energy savings. The types and amounts of fillers added to the polymer matrix directly affect the heat-carrying mechanisms of the composite. In this study, the effects of different types of fillers reinforced into the Polyamide-6 (PA6) matrix on thermal conductivity are comprehensively evaluated, and changes in phonon transport, chain mobility, and amorphous–crystalline structures are analyzed. In particular, the mechanisms by which the addition of boric acid decreases thermal conductivity are examined. In addition, the thermal conductivity effects of fillers such as silica, clay-based fillers, talc, and calcium carbonate are investigated. Thus, by revealing how different filler types influence dispersion within the PA6 matrix, interfacial interactions, and the crystalline structure, the fundamental parameters that determine the thermal performance of the material are assessed. The findings obtained provide guidance for designing target thermal properties in PA6 composites and emphasize the importance of appropriate filler selection, especially in engineering applications requiring thermal management.

Keywords: Polymer Composite, Polyamide-6, Thermal Conductivity

Introduction

Polymer-based composite materials are widely preferred in a broad range of applications—from automotive and defense industries to electronic devices and insulation systems—due to their light weight, formability, and chemical resistance (Tsekmes et al., 2013). Since polymer matrices typically consist of a combination of semicrystalline and amorphous regions, phonon transport is affected by structural irregularities, and their thermal conductivity generally falls within the range of ~0.1–0.4 W/m·K (Tan & Zhang, 2024; Li et al., 2022).

In this context, *thermal conductivity* is a fundamental thermophysical parameter that represents the ability of a material to conduct heat energy and holds critical importance in applications requiring effective thermal management (Variyenli & Arslan, 2017).

Heat transfer is a fundamental process that enables the transport of energy from one region to another, and this transfer occurs through three distinct mechanisms depending on the structural characteristics of the material and environmental conditions. As illustrated in Figure 1, these mechanisms are conduction, convection, and radiation. The effectiveness of each mechanism is governed by factors such as the phase of the material (e.g., solid, liquid, or gas), its structural organization, and intermolecular interactions (Incropera et al., 2007; Çengel & Ghajar, 2015).

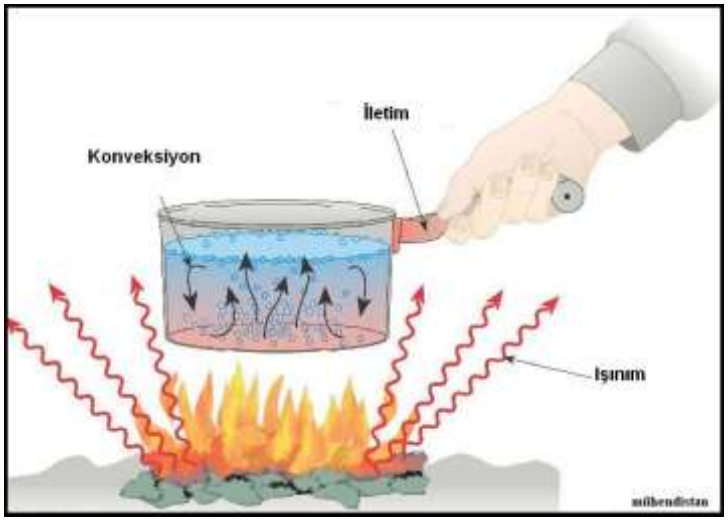

Figure 1. Types of heat transfer (Yeşilata, B., 2007)

For a solid material to conduct heat, the temperature within the material must vary with position; in other words, the temperature distribution must be non-uniform. Put differently, heat conduction in a solid becomes possible only when the temperature gradient within the material is non-zero, which is a direct consequence of the Second Law of Thermodynamics. Fourier's law of heat conduction states that the heat flux passing through a surface per unit time is directly proportional to the temperature gradient within the material. Therefore, in a solid medium, the greater the temperature difference, the higher the amount of heat transferred accordingly.

$$q = -k\,(dT/dx) \quad \ldots\ldots\ldots\ldots \quad (1)$$

In Equation (1):

- **q:** The heat flux per unit area (heat flux density), expressed in W/m².
- **k:** The thermal conductivity of the material, representing its ability to conduct heat; its unit is W/m·K.
- **T:** The temperature field as a function of position (T = T(x)), expressed in K or °C.

- **x:** The spatial coordinate defined along the direction of heat transfer (m).

The negative sign in the equation emphasizes that heat always flows from regions of higher temperature to regions of lower temperature, indicating that the direction of heat flux is opposite to the temperature gradient. In other words, if the temperature decreases in the x-direction ($dT/dx < 0$), the resulting heat flux q is positive, implying that heat is transferred in the positive x-direction. This formulation represents a fundamental heat conduction model valid for a homogeneous and isotropic solid under one-dimensional, steady-state conditions with negligible internal heat generation (Incropera et al., 2007; Çengel & Ghajar, 2015; Yeşilata, 2007).

Development

1. Thermal Conductivity Mechanism in Polymer Composites

Heat transfer in polymer composites occurs primarily through chain vibrations (phonon transport), which distinguishes them from metals and ceramics where heat conduction is dominated by free electrons or lattice vibrations with minimal scattering (Wang et al., 2019). Due to the electrically insulating nature of polymers, the contribution of free electrons to heat transfer is negligible; therefore, thermal conduction mainly takes place through the propagation of phonons generated by vibrational modes of polymer chains (Tan & Zhang, 2024; Wang et al., 2019).

In crystalline regions, the ordered arrangement of polymer chains allows phonons to propagate more continuously, whereas in amorphous regions, chain irregularities, voids, and bond-angle distortions increase phonon scattering and thereby limit heat transfer (Kohutiar et al., 2025). Consequently, an increase in the degree of crystallinity is expected to enhance thermal conductivity, while an increase in amorphous content generally leads to a decrease in conductivity (Beyaz, 2022).

Figure 2 schematically illustrates a typical polymer morphology consisting of crystalline and amorphous regions. Crystalline domains represent areas where the chains are aligned in an orderly and periodic manner, whereas amorphous regions correspond to zones in which the chains are arranged in a more irregular and random configuration (Huang et al., 2018). The relative ratio of these two phases plays a crucial role in determining phonon transport within the polymer and, consequently, its overall thermal conductivity.

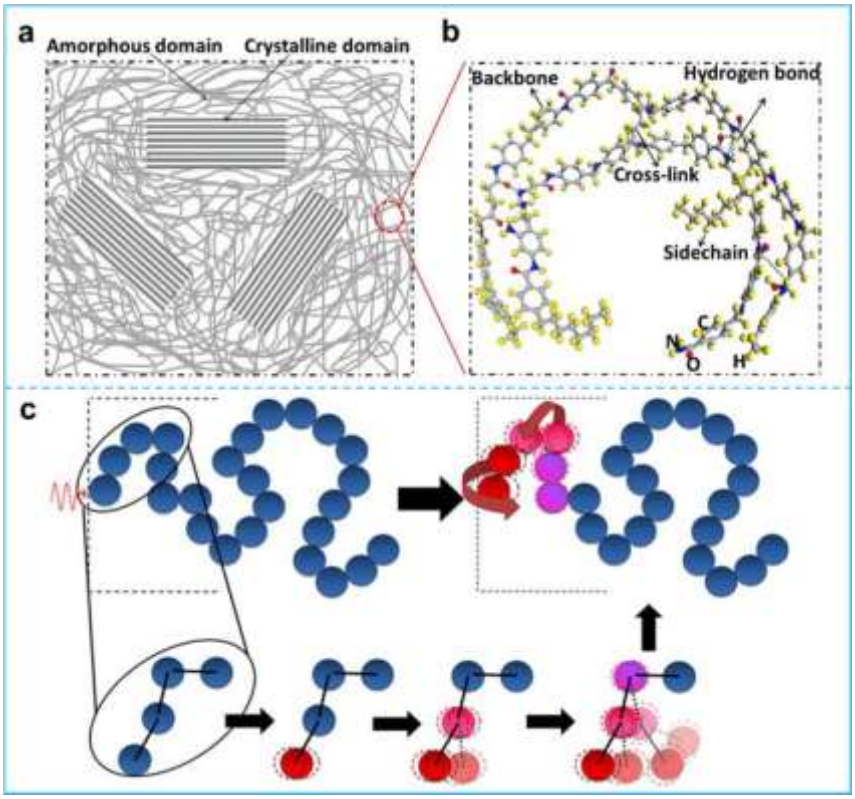

Figure 2. Schematic diagrams of a polymer: (a) morphology of a polymer consisting of crystalline and amorphous regions, (b) structure of a polymer chain, and (c) thermal conductivity mechanism in an amorphous polymer (Huang et al., 2018; Burger et al., 2016).

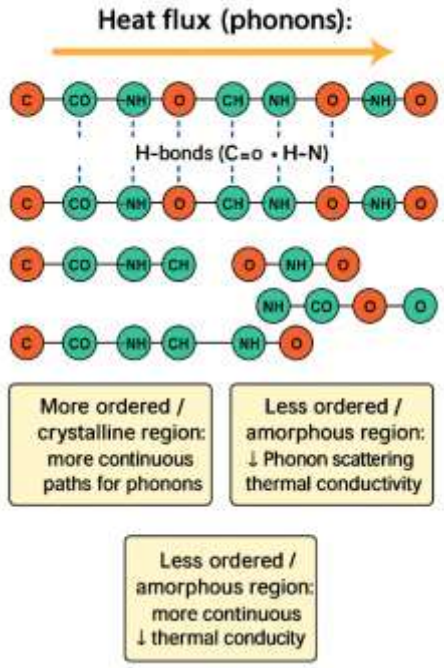

Figure 3. Schematic representation of the thermal conductivity mechanism through hydrogen bonding between Polyamide-6 (PA6) chains.

In Figure 3, phonon propagation (lattice vibrations responsible for heat transport) along PA6 chains is more continuous in ordered crystalline regions, where the chains are more linear and closely packed. In contrast, amorphous regions exhibit greater chain irregularity, conformational variations, and void formation; these factors increase phonon scattering and consequently reduce thermal conductivity. Interchain C=O···H–N hydrogen bonds enhance structural stability, yet simultaneously introduce interfacial resistance along phonon transport pathways, thereby contributing to the limitation of heat transfer. The schematic illustration demonstrates that the combined presence of crystalline and amorphous domains in PA6 plays a decisive role in determining its thermal conductivity.

Fillers incorporated into the polymer matrix may either enhance or restrict phonon transport. This dual effect depends on various parameters, including the intrinsic thermal conductivity of the filler, its compatibility with the matrix, interfacial behavior, particle size, and dispersion morphology within the composite. In the first case, a filler may disrupt phonon pathways within the polymer by introducing additional scattering centers. Structurally incompatible fillers or mineral-based materials with low thermal conductivity interrupt phonon motion and lead to a reduction in overall thermal conductivity (Çeliker, 2020; Kırbaş, 2021).

Conversely, when the filler possesses intrinsically high thermal conductivity, it may increase heat transfer within the polymer matrix. Fillers such as carbon nanotubes, graphene, graphite, and boron nitride known for their high conductivity form continuous heat-transfer pathways once a sufficient loading level is reached, enabling phonons to move faster and with less scattering compared to transport along polymer chains (Tan & Zhang, 2024; Kohutiar et al., 2025).

In a semicrystalline polymer such as PA6, boric acid addition can modify the crystalline–amorphous ratio and increase phonon scattering. These findings indicate that boric acid is a promising filler candidate for polymer composite design aimed at thermal insulation applications (Beyaz, 2022).

2. Polyamide-6 with Boric Acid Additives

Polyamide 6 (PA6) is a linear thermoplastic composed of repeating –NH–$(CH_2)_5$–CO– units, and its semicrystalline structure, mechanical strength, and thermal stability originate from the dense network of hydrogen bonds between chains. The stacking of amide groups (C=O···H–N) in a layered arrangement governs the formation of the α and γ crystalline phases, and this crystal morphology directly influences both the thermal conductivity and the combustion behavior of the material (Seguela, 2020; Wu, Liu & Berglund, 2002). The efficiency of heat conduction along polymer chains—based on phonon transport—is also strongly associated with the degree of crystallinity, chain alignment, and the continuity of the hydrogen-bonding network (Xu, Chen, Zhou & Li, 2018).

Boric acid, also known as hydrogen borate or orthoboric acid [H_3BO_3 or $B(OH)_3$], is a boron compound containing three hydroxyl groups and exhibiting marked Lewis acidity despite its weak Brønsted acidity. The –$B(OH)_3$ unit in the molecule can act as both a hydrogen-bond donor and acceptor. It is also known to react with –OH groups present in polysaccharides and polyols to form borate esters (B–O–C) (Zhang et al., 2020; Doğan et al., 2021; Uğurlu, 2020). At elevated temperatures, boric acid undergoes stepwise dehydration, forming metaboric acid and ultimately a glassy boron oxide (B_2O_3) phase. This phase is effective in flame-retardant systems through a condensed-phase mechanism by forming a dense and rigid char layer (Doğan et al., 2021; Mohd Sabee et al., 2022).

When boric acid or boric-acid-modified fillers are incorporated into the PA6 matrix, the interactions can be examined at two fundamental levels:

(i) hydrogen-bonding/coordination interactions at the macromolecular level under processing and service conditions, and

(ii) formation of boron-containing glassy/charred structures in the condensed phase during thermal degradation or combustion.

At the first level, the carbonyl (C=O) and amide N–H groups on PA6 chains are the primary functional sites capable of forming strong hydrogen bonds with the –OH groups of boric acid. In the literature, it has been demonstrated through FTIR measurements that in PA6/clay nanocomposites, clay layers modify the conformation of amide groups, weaken the hydrogen-bonding network, and promote the transition from the α-phase to the γ-phase (Wu et al., 2002). Similarly, in systems containing boric acid, hydrogen bonds of the –NH···O–$B(OH)_2$ and C=O···H–O–B type may compete with the classical interchain C=O···H–N interactions, thereby modifying local crystal order and hydrogen-bonding density. This allows fine-tuning of PA6 crystallization kinetics and the degree of crystallinity, particularly when low levels of boric acid or boric-acid-modified fillers are used. However, because direct hydrogen-bond analyses specifically for PA6/boric acid systems are limited, these interpretations largely rely on generalized FTIR and structural data from analogous systems (PA6/clay, PA66/boron-containing networks, etc.) (Wu et al., 2002; Mohaddes et al., 2014).

At the second level, condensed-phase reactions involving boric acid directly or indirectly come into play. Zhang et al. (2020) demonstrated that chemical modification of lignocellulose with boric acid results in the formation of borate structures containing B–O–C linkages, and when this borated lignocellulose is used with PA6, the thermal stability of lignocellulose increases and the onset degradation temperature of composites rises. XPS and FTIR analyses indicate that boric acid is primarily retained through covalent bonding within the lignocellulosic matrix, while its interactions with PA6 are predominantly through hydrogen bonding and physical interlocking. In such bio-composites, enhanced interfacial interactions between the PA6 phase and the borated filler can contribute to restricting crack propagation and limiting diffusion into the gas phase during thermal degradation (Zhang et al., 2020).

The incorporation of boric acid into PA6 systems has been studied particularly in flame-retardant textile structures (Selvakumar et al., 2012; Guo, 2023) and biomedical nanofiber applications (Nur et al., 2021). Flame-retardant performance has also been investigated in PA6 with the addition of boric acid and boron oxide together with organophosphorus compounds (Polat & Kaynak, 2016).

Yılmaz et al. (2011) reported that boron-containing compounds such as zinc borate and boro-phosphate added to PA6/melamine cyanurate composites can enhance flame retardancy by modifying the char structure, although depending on the type and amount of additive, they may also reduce the onset degradation temperature. Doğan et al. (2021) emphasized that boron compounds generally act in the condensed phase by forming a hard protective layer with B_2O_3 or boro-phosphate character, strengthening the char. These findings indicate that in PA6 systems, boric acid does not typically form covalent bonds with the polymer chain but creates ionic or coordinative networks by interacting with polar products and phosphorus-containing species generated during degradation. Similarly, in a study on PA66, boric acid–phosphoric acid esters were shown through FTIR analysis to form a denser and more thermally stable char layer (Mohaddes et al., 2014).

When evaluating the thermal conductivity of PA6 systems containing boric acid, it must be considered that heat transfer in polymers is predominantly governed by phonon scattering, and that chain order, crystallinity, and phase boundaries determine these scattering processes (Xu et al., 2018). Although the number of studies quantitatively investigating the direct "boric acid–PA6 thermal conductivity relationship" is limited in the literature, it is generally accepted that any additive that modifies filler/matrix interfaces and crystallinity can increase phonon scattering and thereby reduce thermal conductivity. Moreover, a decrease in crystallinity and disruption of the hydrogen-bonding network in PA6 restrict the orderly propagation of phonons. Such structural irregularities can effectively contribute to reducing thermal conductivity when boric acid or boric-acid-modified fillers are used in suitable formulations (Seguela, 2020; Wu et al., 2002).

3. Effect of Other Inorganic Fillers

Inorganic fillers used in polymer composites are critical additive components that directly influence the thermal and structural behavior of polymer chains. The effects of these fillers on the polymer matrix arise from multiple parameters, including particle morphology, surface chemistry, crystalline structure, and matrix filler interfacial interactions. The primary influence of inorganic fillers on thermal conductivity is associated with the phonon transport pathways they create within the composite, the interfacial thermal boundary resistance (TBR), and their ability to form continuous heat-conduction networks (Xu, Chen & Li, 2018).

Inorganic fillers with high thermal conductivity such as boron nitride (h-BN), alumina (Al_2O_3), magnesium oxide (MgO), and graphite can enhance the thermal conductivity of the polymer matrix by forming a continuous solid-phase heat-transfer network once a sufficient filler loading is achieved. These fillers facilitate phonon propagation with reduced scattering due to the strong atomic bond energies inherent to their crystal structures. Numerous studies have reported that in h-BN–reinforced PA and epoxy composites, thermal conductivity increases significantly when the filler content reaches the critical volume fraction required for solid-phase continuity (Shtein et al., 2015).

In contrast, low-conductivity inorganic fillers such as silica (SiO_2), talc, kaolin, clay minerals, and calcium carbonate ($CaCO_3$) operate through a mechanism that increases phonon scattering within the composite. These particles disrupt the regular heat-transfer pathways of polymer chains, creating barrier effects along phonon transport routes. Therefore, fillers such as SiO_2 and $CaCO_3$ are known to contribute to decreasing thermal conductivity (Khanam et al., 2014). Additionally, when the surface energy of such fillers differs from that of the polymer matrix, interfacial thermal resistance increases, further reducing heat-transfer capacity (Ruan et al., 2023).

The homogeneity of filler dispersion within the polymer is another critical parameter governing the thermal behavior. Homogeneously distributed fillers provide a more uniform microstructure for heat conduction, whereas particles prone to agglomeration create localized thermal barriers that interrupt phonon flow (Gu et al., 2019). This phenomenon is particularly important for nanoscale fillers, as their high surface area can increase interfacial thermal resistance.

Fillers such as talc and kaolin, which exhibit nucleating effects, may increase the crystallization temperature in semicrystalline polyamide matrices, promoting more ordered and distinct crystalline domains. Differential scanning calorimetry (DSC) analyses have shown that the addition of talc and kaolin to PA6/carbon fiber composites elevates crystallization temperature and improves crystal perfection (Jianfeng et al., 2020). Conversely, some nano- and microscale fillers that possess irregular surface structures, strongly interact with polymer chains, restrict

chain mobility, or form incompatible interfacial regions can hinder crystallization and reduce the degree of crystallinity. As a result, the phonon transport pathways available in the crystalline phase become limited, leading to reduced thermal conductivity (Nair et al., 2005; Shi et al., 2010).

In summary, the influence of inorganic fillers added to polymers cannot be explained through a single mechanism. The type of filler, particle size, surface activity, interfacial bonding behavior, and the resulting microstructural composition collectively determine the final thermal performance of the composite. Therefore, achieving the desired thermal properties requires the careful selection of filler type, implementation of appropriate surface-modification treatments, and strict control of filler dispersion within the matrix.

4. Mechanisms for Reducing Thermal Conductivity

Polymer-based materials inherently possess low thermal conductivity (typically in the range of ~0.1–0.4 W/m·K), and for this reason they are widely used in thermal insulation and thermal-management applications (Breitkopf, 2024). Reducing the thermal conductivity of polymer composites is fundamentally achieved by controlling microstructural and chemical mechanisms that restrict phonon transport and interrupt heat-flow pathways. The primary mechanisms that reduce thermal conductivity in polymers and polymer composites are summarized below.

4.1 Phonon Scattering and the Increase of the Amorphous Phase

In electrically insulating polymers, heat transfer is predominantly governed by lattice vibrations (phonons). Therefore, thermal conductivity is directly related to the phonon mean free path and scattering frequency (Choy, 1977; Wei, 2021; Xu et al., 2018). In amorphous regions, chain irregularities, bond-angle deviations, and topological disorder increase phonon scattering, thereby reducing thermal conductivity. In crystalline regions, by contrast, the polymer chains are more regularly aligned, allowing phonons to propagate over relatively longer distances with fewer scattering events.

Cahill's studies on amorphous solids demonstrate that as structural disorder increases, thermal conductivity approaches a lower bound referred to as the "minimum thermal conductivity" (Cahill, 1987). Consequently, increasing the amorphous phase fraction in a polymer composite can be considered a fundamental strategy for enhancing phonon scattering and reducing thermal conductivity.

4.2. Reduction of Crystallinity and Disruption of Chain Orientation

The thermal conductivity of polymers is closely associated with their degree of crystallinity, crystal grain size, and chain orientation. High crystallinity and strong chain alignment tend to increase thermal conductivity by creating more continuous lattice pathways through which heat flux can propagate (Choy, 1977; Xu, 2020).

In contrast, any structural modification that:

- reduces crystallinity,
- increases crystal/amorphous interfaces,
- disrupts chain orientation

hinders phonon transport between crystalline domains and decreases the overall thermal conductivity. Xu (2020) emphasizes that when crystallinity and chain orientation are reduced in polymers, thermal conductivity decreases significantly, and amorphous interphase regions play a critical role in phonon scattering.

Modifying crystallization kinetics through filler incorporation, reducing crystal size, or partially suppressing the crystalline phase are commonly employed strategies to lower thermal conductivity.

4.3. Interfacial Thermal Resistance

In polymer composites, heat transfer occurs not only within the matrix but also across the matrix–filler interfaces. At these regions—where two phases with different elastic properties, densities, and phonon spectra come into contact—interfacial thermal resistance (ITR) is generated. This resistance is one of the primary factors limiting the overall thermal conductivity of the composite, particularly when low-conductivity or weakly bonded fillers are present (Ruan et al., 2020; Gu et al., 2021).

Ruan et al. (2020), in their review on thermally conductive polymer composites, demonstrated how different filler types (platelet-like, fibrous, particulate) influence interfacial thermal resistance and showed that in systems with numerous interfaces, ITR plays a dominant role in reducing thermal conductivity.

From the perspective of reducing thermal conductivity:

- increasing the number of matrix/filler interfaces,
- weak or incompatible interfacial bonding,
- the presence of voids and defects at the interface

all enhance phonon reflections and scattering, thereby restricting heat flow. For this reason, multiphase structures with a high number of interfaces may be advantageous in designs targeting low thermal conductivity.

4.4. Voids, Porosity, and Low-Density Regions

One of the most effective mechanisms for reducing thermal conductivity is the formation of voids and pores. Voids containing stagnant gas phases or vacuum possess significantly lower thermal conductivity than the solid polymer phase. Therefore, the presence of:

- micro-/mesoscopic voids within the matrix,
- closed-cell porous structures,
- low-density phases

reduces the effective thermal conductivity of the composite. In polymer foam systems, decreases in density and increases in porosity have been reported to reduce thermal conductivity by more than 50% (Kırbaş et al., 2021).

In porous polyurethane systems, the addition of boric acid has been shown to significantly decrease both density and thermal conductivity; as the filler content increases, the thermal insulation performance of the composite improves (Kırbaş et al., 2021). These findings indicate that boron compounds can reduce thermal conductivity through promoting pore formation and stabilizing low-density phases.

4.5. Chemical Interactions, Chain Mobility, and Bonding

Recent studies have shown that chemical interactions and hydrogen bonding between polymer chains and the filler phase also influence thermal transport. When:

- hydrogen bonds,
- coordinative bonds,

- covalent crosslinks

are formed between polymer chains and the filler surface, chain mobility can be restricted, the local structure may become more disordered, and the continuity of phonon transport can be disrupted (Wei, 2021; Mukherji, 2024). Such chemical interactions become particularly significant in systems where hydrogen-bond-forming polymers (e.g., polyamides) interact with oxygen- or hydroxyl-containing inorganic fillers (e.g., boric acid, borate derivatives). In this way, microstructural disorder and the number of interfacial regions increase, enabling a reduction in thermal conductivity.

4.6. Use of Low Thermal Conductivity Fillers: Boric Acid-Based Systems

Another approach to reducing thermal conductivity is the incorporation of fillers that inherently possess low thermal conductivity. Polymer composites containing boric acid and various boron minerals have been reported to be used for both thermal and electrical insulation purposes. Çeliker et al. (2020) demonstrated that in composites produced by adding boric acid and paper-mill sludge to a polyester matrix, the thermal conductivity coefficient decreased as the filler content increased, rendering the thermo-mechanical performance suitable for insulation applications. Ersoy (2007) reported that composites produced by incorporating boric acid and different boron minerals into unsaturated polyester resin exhibited improved electrical and thermal insulation properties, indicating that such systems can be employed for insulation purposes. Kırbaş et al. (2021) found that the addition of boric acid to rigid polyurethane foams resulted in more than a 50% reduction in thermal conductivity compared to neat polyurethane; this decrease was attributed to both increased porosity and the formation of boron-containing phases with inherently low thermal conductivity.

These findings demonstrate that boric acid and boron compounds can serve as effective fillers for reducing thermal conductivity when combined with appropriate polymer matrix selection and processing conditions. Similarly, with the incorporation of boric acid into a PA6 matrix, a reduction in thermal conductivity is expected through mechanisms such as an increased number of interfaces, partial suppression of crystallinity, disruption of chain order, and the possible formation of micro-voids.

Conclusion

In this study, the effects of various fillers incorporated into a Polyamide-6 (PA6) matrix on thermal conductivity were comprehensively evaluated, and heat-transfer mechanisms were examined holistically in terms of phonon transport, crystallinity, interfacial resistance, and filler–matrix interactions. Considering that heat transfer in polymers largely depends on the mean free path of phonons, the influence of filler type on polymer chain order and interfacial structure emerges as a critical factor determining the final thermal performance of the composite.

The findings demonstrated that inorganic fillers with low thermal conductivity (such as boric acid, silica, $CaCO_3$, and clay minerals) reduce the thermal conductivity of the PA6 matrix by increasing phonon scattering. The weak compatibility between these fillers and polymer chains, along with the interfacial thermal resistance they generate, disrupts phonon continuity; furthermore, the increase in the amorphous phase further restricts heat-transfer pathways. Microstructural modifications that reduce crystallinity, break chain orientation, and increase phase boundaries were found to be effective in achieving low thermal conductivity.

The effects of boric acid on PA6 became evident at both the microstructural and chemical-interaction levels. Hydrogen bonds formed between the –OH groups of boric acid and the C=O and N–H functional groups of PA6 chains weakened the classical interchain hydrogen-bond

network and partially suppressed crystallinity. This led to a more disordered phonon transport environment, contributing to reduced thermal conductivity. Additionally, the boron oxide phase generated through the stepwise dehydration of boric acid at processing temperatures created low-conductivity regions and potential micro-voids within the matrix, serving as additional mechanisms that hinder heat flow.

Compared to other filler types, boric acid proved to be a compatible additive for PA6 in applications specifically aiming to reduce thermal conductivity. Unlike highly conductive fillers such as BN, graphite, or CNTs, boric acid acted by forming barriers that interrupt phonon pathways and prevented the formation of continuous thermal networks, thereby enhancing structural disorder and contributing to the desired thermal-insulation performance.

In conclusion, reducing thermal conductivity in PA6 composites is achievable through the combined control of multiple mechanisms, including increasing the amorphous phase, enhancing interfacial thermal resistance, promoting micro-void formation, and tailoring filler–matrix interactions. This study provides important scientific insight into the phonon-scattering effects of boric acid in PA6 and highlights its potential for applications requiring low thermal conductivity, such as thermal insulation, ammunition casings, avionics housings, and protective electronic structures. The findings indicate that with proper filler selection and microstructural engineering, the desired thermal performance can be effectively designed in PA6 composites.

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ÖN ALAŞIM + ÖN KARIŞIMLI ALUMIX 123 TOZUN SİNTERLEME VE ALAŞIMLAMA DAVRANIŞININ İNCELENMESİ

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ÖZET

Ticari Alumix 123 tozu, kimyasal içerik bakımından dövme Al2014'e benzeyen alüminyum alaşımı metal tozudur. Bu toz, havacılık ve otomotiv endüstrisi başta olmak üzere imalat sektöründe kullanılan başlıca alaşımlardan biridir. Ancak üretim ve piyasaya arz sürecinde AlSiMg ön alaşımlı metal tozları ile birlikte, Al+4,5Cu içeriği ile ön karışımlı toz olarak hazırlanır. Bu durum ise gerek sinterleme veya gerekse sıcak presleme sürecinde Al-%4,5Cu alaşımının sağlanmasında bazı problemler oluşturabilmektedir. Bu çalışmada, Alumix 123 tozunun farklı sıkıştırma basınçlarında soğuk preslenmesi sonrası üç farklı sıcaklıklarda bir saat süre ile sinterlenmesi ile oluşan mikroyapılar ve alaşımlanabilme özelliği karakterize edilmiştir. Optik ve taramalı elektron mikroskop (SEM) çalışmaları ile üretilen toz metal (TM) parçaların mikroyapıları ve sinterlenebilirliği incelenmiştir. Özellikle ön karışımlı tozun oluşturduğu Al-Cu alaşımlama durumu ve oluşan fazlar, SEM-EDS analizleri ile incelenmiştir. Deney sonuçları göstermiştir ki, en yüksek sıkıştırma basıncında (500MPa) ve 570 °C sinterleme sıcaklığında en yüksek yoğunluk sağlanmıştır. Minimum sıkıştırma basıncı olan 300 MPa'da ve 500 °C sinter sıcaklığında ise minimum ham ve sinterleme sonrası yoğunluk sağlanmıştır. Sinterleşme problemi ile oluşan gözeneklilik ve düşük sinterleme sıcaklığı Al4,5Cu alaşımlanma durumunu olumsuz etkilemiştir. En yüksek sıcaklık olan 640 °C'deki sinterleme işleminde ise yer yer bu Al-Cu konsantrsayon farklılıkları nedeniyle oluşan ötektik oran sebebiyle TM malzeme içinde kısmi sıvı fazların oluştuğu görülmüştür.

Anahtar kelimeler: Toz Metalurjisi, Alumix 123, Sinterlenebilirlik, Alaşımlama, Mikroyapı

INVESTIGATION OF SINTERING AND ALLOYING BEHAVIOR OF PREALLOY + PREMIXED ALUMIX 123 POWDER

ABSTRACT

Commercial Alumix 123 powder is an aluminum alloy metal powder similar in chemical composition to wrought Al2014. This powder is one of the primary alloys used in manufacturing, particularly in the aerospace and automotive industries. However, during the production and marketing processes, it is prepared as a premixed powder with an Al+4.5%Cu content, along with AlSiMg prealloyed metal powders. This can create some problems in obtaining the Al-4.5%Cu alloy during both the sintering and hot pressing processes. In this study, the microstructure and alloying properties of Alumix 123 powder were characterized by cold pressing under different compression pressures and sintering at three different temperatures for one hour. The microstructure and sinterability of the produced powder metal (PM) parts were investigated using optical and scanning electron microscope (SEM) studies. In particular, the Al-Cu alloying state of the premixed powder and the resulting phases were investigated by SEM-EDS analyses. Experimental results showed that the highest density was achieved at the highest compression pressure (500 MPa) and sintering temperature of 570 °C. The minimum density, both as-cast and after sintering, was achieved at the minimum compression pressure of 300 MPa and sintering temperature of 500 °C. The porosity resulting from the sintering problem and the low sintering temperature negatively affected the Al4.5Cu alloying process. However, during the sintering process at the highest temperature of 640 °C, partial liquid phases were observed to form within the PM material due to the eutectic ratio resulting from these Al-Cu concentration differences.

Keywords: Powder Metallurgy, Alumix 123, Sinterability, Alloying, Microstructure

1.GİRİŞ

Alüminyum alaşımları günümüzde çelikten sonra en çok kullanılan metalik mühendislik malzemeleridir (Altenpohl, D.G., 1980). Yüksek dayanım ve hafiflik özellikleri sayesinde çoğunlukla havacılık ve otomotiv gibi endüstrilerde kullanılmaktadır (Rudinsky et al., 2016), (C. Padmavathi, A. Upadhyaya, D. Agrawal, 2011). Günümüz teknolojisine bağlı olarak gelişen malzeme bilimi, endüstrideki gelişmelere paralel olarak önemli bir yer tutmaktadır. İmalatçılar, daha hafif ve daha mukavemetli yapılar elde etmek için maliyeti yüksek araştırmalar yapmaktadırlar. Alüminyum alaşımlarının çeşitli sinterleme teknikleriyle toz parçacıklarının konsolidasyonu yoluyla bu tür endüstriler için küçük parçalar üretmede etkili olduğu kanıtlanmıştır. Toz metalurjisi yöntemleri günden güne gelişmekte olan yöntemlerden biridir.

Alümix123 tozunun ana matrisi olan Al, ağırlıkça yaklaşık %94 oranında bulunur. Karışım elementi olan Cu %4,5 oranında bulunabilir. Diğer alaşım elementlerinden Si %0,8, Mg %0,5 oranındadır (Judge et al., 2017). Ön alaşımlı tozlar mikroyapı ve kimyasal özellikler bakımından birbiri ile aynıdır, alaşım tamamen homojendir. Alümix123 tozu, alaşımlandırılmış toz partiküllerine ağırlıkça %4,5 oranında saf bakır elementi eklenerek oluşturulan heterojen bir karışımdır (Özçatalbaş et al., 2018; Judge et al., 2017).

Toz metalurjisi üretim yönteminin amacı, metal tozlarını ergitmeden basınç ve sıcaklık yardımıyla dayanıklı cisimler haline sokmaktır. Toz metal partiküllerin üretimi, karakterizasyonu, sıkıştırılması ve sinterlenmesi aşamalarını kapsar. Deneyde kullandığımız Alümix123 toz malzeme, en yaygın toz üretim metodu olan atomizasyon ile üretilmiştir. Alüminyum esaslı toz metalurjisi uygulamalarında, özellikle Alumix 123 gibi ön karışımlı tozların sinterleme öncesi özelliklerini iyileştirmek ve oksit tabakasını kırmak amacıyla Mekanik Alaşımlama (MA) yöntemi kullanılabilmektedir (Delibalta, C. G., & Özçatalbaş, Y., 2018, ISLAC). Üretilmiş tozlar belirlenen basınçta sıkıştırılarak ham mukavemet kazandırılır. Sıkıştırma aşamasında parçacıklar arası bağ oluşmaz ve mekanik bir işlemdir, yaygın olarak oda sıcaklığında yapılır. Sinterleme ise bu üretim yönteminin en kritik noktasıdır. Bu işlemde malzeme ergime sıcaklığının altında, belirlenen sıcaklıkta ve sürede ısıtılarak atomlar arası bağlar oluşturulur. Böylece malzeme sertlik ve mukavemet kazanır. Sinterleme anında bir atom saniyede 10^14 kez titreşir. Katı hal ve sıvı hal sinterlemesi olmak üzere iki türü vardır. Eğer kullanılan toz bir karışım veya alaşım şeklinde ise tüm malzemelerin ergime sıcaklığının altında sinterleme yapıldığında buna katı hal sinterlemesi denir. En az bir alaşım elementinin ergime noktasının üzerinde sinterleme yapıldığında sıvı faz görmek mümkündür ve buna sıvı hal sinterlemesi denir (Özçatalbaş et al., 2018). Alümix123 tozu kimyasal kompozisyon bakımından dövme AAl2014 alaşımına benzer.

Alüminyum alaşımların toz metalurjisi ile üretiminde genellikle elementel tozlar, önalaşımlı tozlar veya ön karışımlı tozlar kullanılır. Difüzyonla birleştirilmiş alüminyum tozlarına literatürde rastlanılmamakla birlikte, alüminyum tozlarının oksitlenmesinin engellenmesi için polimer esaslı kaplamalarla kaplandığı bazı çalışmalar mevcuttur (Gökçe vd., 2017).

Bu çalışmada, Alumix 123 tozunun farklı basınçlarda soğuk preslenmesi ve sonrası üç farklı sıcaklıklarda bir saat sinterlenmesi ile oluşan mikroyapılar ve alaşımlanabilme özelliği karakterize edilmiştir.

2.MALZEME VE METOD

2.1 Malzeme

Bu çalışmada kullanılan toz malzeme atomizasyon yöntemiyle üretilmiştir. Kimyasal kompozisyon bakımından AA2014 malzemeye eşdeğerdir (Al, Cu, Si, Mg). AlSiMg ön alaşımlı alüminyum tozu içerisine, ağırlıkça %4,5 oranında Cu tozu karıştırılarak ön karışımlı toz elde

edilmiştir. Kimyasal bileşimi Çizelge 1'de verilen, Eckart Granulers tarafından üretilen Ecka Alumix123 olarak bilinen ön-karışımlı alüminyum esaslı tozdur ve yağlayıcı içermemektedir.

Çizelge.1: Deneyde kullanılan malzemenin kimyasal bileşimi (% ağırlık)

Alaşım	Al	Cu	Si	Mg
AlCuSiMg	94,3	4,5	0,7	0,5

2.2 Sıkıştırma

Sıkıştırma işlemi sinterleme öncesi toz parçacıkların mekanik olarak birleşmesiyle ham mukavemet ve ham yoğunluk sağlanarak şekillendirmek için yapılır. Sıkıştırma işlemi, tek yönlü zımba ile 31mm uzunluğunda ve 13 mm genişliğindeki bir kalıp boşluğunda gerçekleştirilmiştir. Sıkıştırma işlemi Instron marka, tek eksenli hidrolik pres makinesi vasıtasıyla 300, 400, 500 MPa olmak üzere üç farklı basınçta yapılmıştır. Presleme işlemi oda sıcaklığında gerçekleşmiştir.

Sıkıştırma işlemi sonrası numunelerin ham yoğunlukları, boyutları ölçülerek hesaplanan hacimlerine hassas terazide ölçülen ağırlıklarının bölünmesi ile hesaplanmıştır. Sinter sonrası yoğunluk ölçümleri Archimed prensibine göre yapılmıştır.

Sıkıştırma işleminde kullanılan kalıbı yağlamak için çinko stearat ve alkol karışımı kullanılmıştır. Bu yağlayıcının kullanım amacı; presleme sırasında toz parçacıkları ve kalıp arasındaki sürtünmeyi azaltmak, numunenin kalıptan çıkarılmasını kolaylaştırmak ve kalıp ömrünü uzatmaktır.

2.3 Sinterleme

Toz parçacıkların katı halde difüzyonu ile TM malzemeye sertlik ve mukavemet kazandırmak için sinterleme yapıldı. Bunun için 'Protherm Furnaces' marka tüp sinter fırını kullanıldı. Bu işlem, numunelerin oksidasyona uğramaması için kontrollü atmosfer ortamında gerçekleştirilmiştir. Sinterleme süresince fırına devamlı olarak argon gazı gönderilmiş ve ortamda olabilecek oksijeni bağlamak için de numunelerin üst yüzeyleri titanyum granürlerle kapatılmıştır.

Sinterleme işleminin mikroyapıya ve gözenekliliğe etkilerinin araştırılması için üç farklı sıcaklık seçilmiştir. 500, 570 ve 640°C'lerde; tüm numuneler için sinterleme süresi 60 dakika olarak belirlenmiştir. Isıtma hızı 10°C /dk olarak ayarlanmış, numuneler istenilen sıcaklıkta bir saat tutulduktan sonra fırın ortamında yavaş soğumaya bırakılmıştır.

2.4 Optik ve Taramalı Elektron Mikroskop (SEM) Analizi

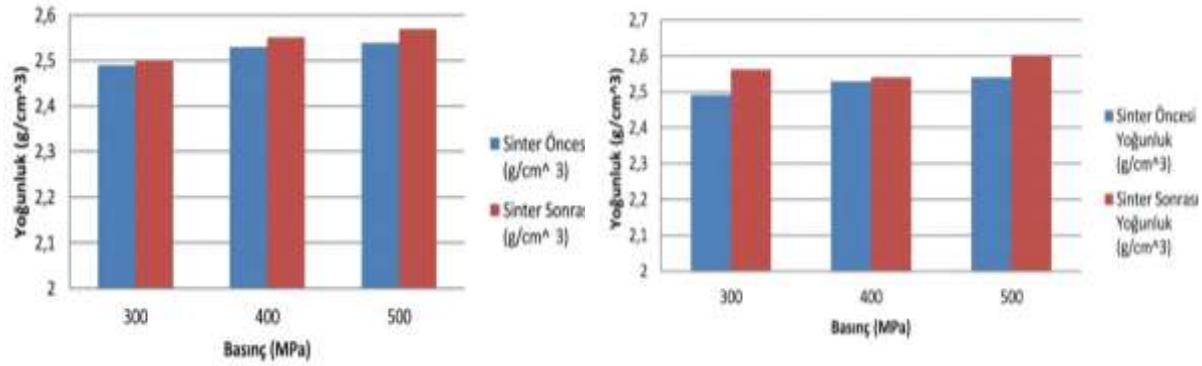
SEM analizinde kullanılacak olan 500 MPa'da preslenen ancak üç farklı sıcaklıkta sinterlenen TM numunelerin yüzeyleri uygun metalografik işlemlerden geçerek hazırlanmıştır. Sırasıyla 400, 800, 1200 gritlik zımparalarda zımparalanmış ve elmas çözelti ile parlatma işlemi yapılmıştır. Mikroyapıyı belirlemek için Kellers çözeltisi hazırlanarak yüzey dağlama işlemi gerçekleşmiştir.

Mikroyapı analizleri taramalı elektron mikroskobunda (SEM) yapılmıştır. SEM analizi esnasında malzeme EDS (Enerji Dağılımlı X-Işını Spektrometresi) analizine tabii tutulmuştur. Böylece yüzeydeki kimyasal kompozisyonlar incelenmiş, Al-Cu konsantrasyon analizleri yapılmıştır.

3. DENEYSEL BULGULAR

3.1 TM Numunelerin Ham ve Sinter Yoğunlukları

Yapılan yoğunluk ölçümlerinde genel olarak sıkıştırma basıncının artmasıyla, yoğunluğun arttığı söylenebilir. Ancak, 400 MPa dan sonra artan sıkıştırma basıncının ham yoğunluğa etkisinin olmadığı görülmektedir. Alumix 123 malzemenin sinterlenme davranışında sıcaklığın artmasıyla yoğunluğun da arttığı gözlenmiştir. 570 °C'de malzemenin sinter sonrası yoğunluğunun en yüksek ve dolayısıyla gözeneklilik oranının düşük olduğu görülmektedir.

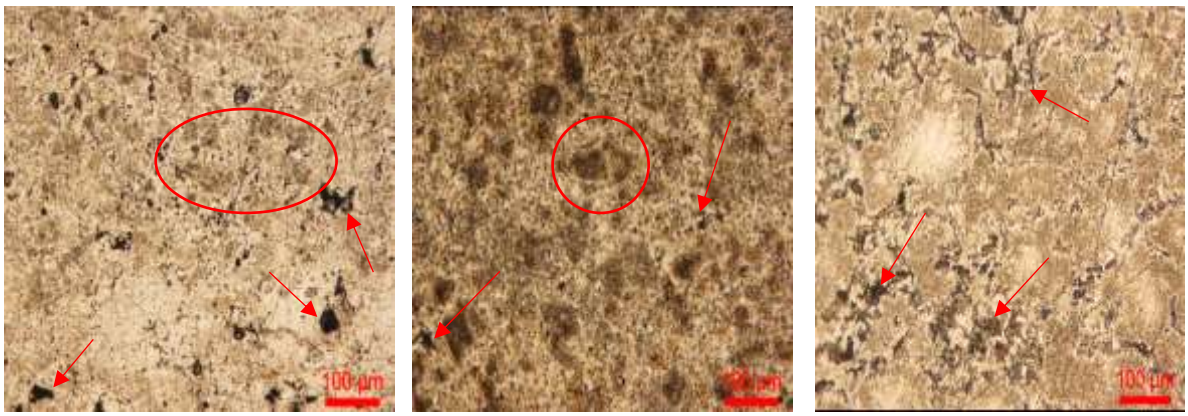


a) 500 °C'de sinterlenmiş b)570 °C'de sinterlenmiş

Şekil 1. TM numunelerin sıkıştırma basıncı ve sinter sıcaklığına bağlı değişen ham ve sinter yoğunlukları a) 500 °C'de b) 570 °C'de sinterlenmiş

3.2 Mikroyapı ve SEM Analizleri

TM numunelerin sinterleme sonrası mikroyapısal değişimleri ile ilgili optik mikroskop görüntüleri Şekil 2'de verilmiştir. Burada özellikle düşük sıcaklıkta sinterleme ile oluşan sinter sonrası gözenekler açıkça görülmektedir (Şekil 2a'da oklarla gösterildi). Bununla birlikte yer yer daha koyu renk tonunda bakırca zengin fazlar da çember içinde gösterilmiştir. Sinter sıcaklığı 570°C olan numunede ise Cu'ca zengin fazlar görülmekle birlikte (Dağlama bu numunede fazla olmuştur) çok daha küçük ve az sayıda gözenek oranı görülmektedir. 640 °C'de sinterlenmiş TM malzemesinde ise çok yoğun olarak muhtemel sıvı faz olumundan kaynaklı mikro boşluklar mevcuttur.

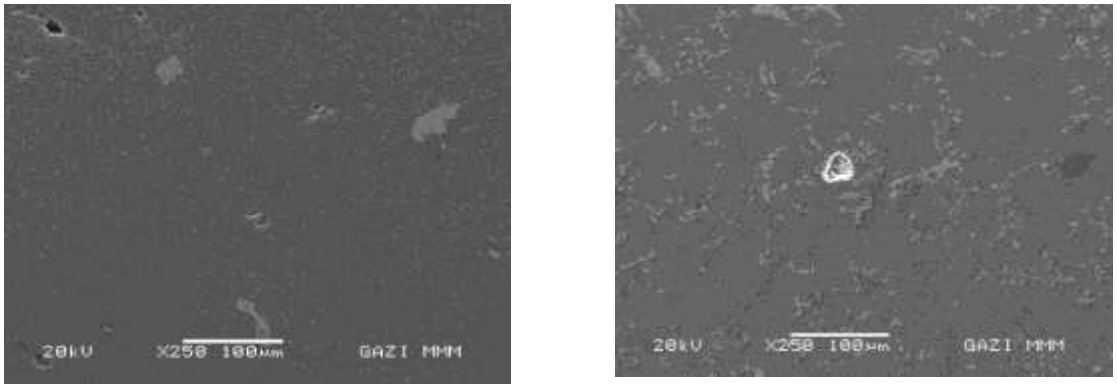


a) 500 °C'de sinterlenmiş b) 570 °C'de sinterlenmiş c) 640 °C'de sinterlenmiş

Şekil 2. 500 MPa basınçta sıkıştırılmış ve farklı sıcaklıklarda sinterlenmiş TM numunelerin mikroyapıları

Şekil 3'de 500°C ve 640°C sıcaklıklarda sinterlenmiş TM numunelerin SEM görüntüleri verilmiştir. Düşük sıcaklıkta sinterlenmiş numunede sinter yetersizliği nedeniyle oluşmuş

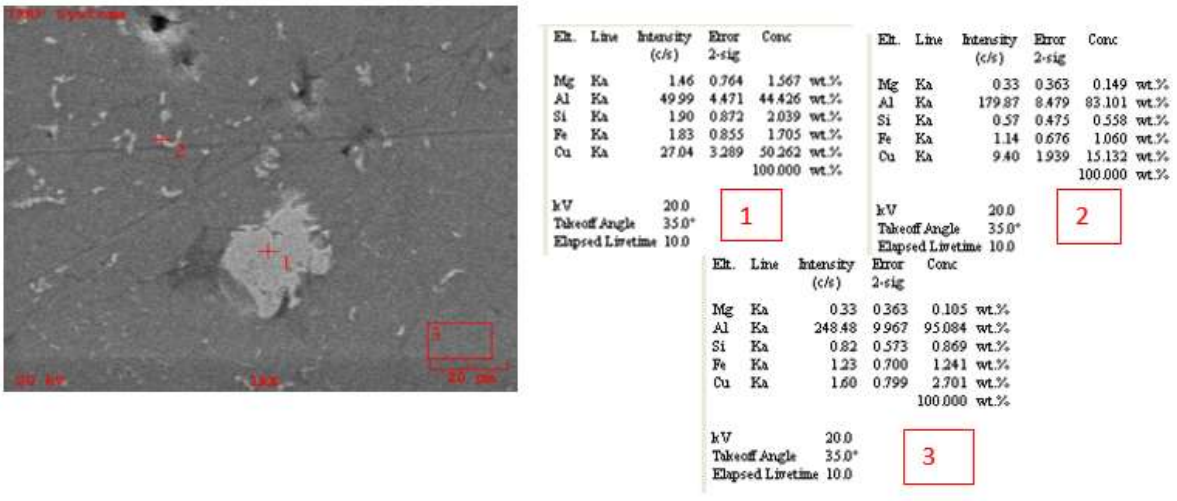
gözenekler açıkça görülmektedir. Ayrıca karışım olarak bulunan Cu parçacıkları da neredeyse orijinal başlangıç formlarını korumakta ve Al matris içinde yeterince çözünmedikleri anlaşılmaktadır. Bununla birlikte özellikle üst kısımlarda az oranda da olsa Cu'ca zengin çökelti fazları dikkat çekmektedir. Bu bakımdan bu sıcaklıkta Al-Cu alaşımla oranının düşük olması muhtemeldir. Ancak Şekil 3b'de durum farklıdır ve Al matris de neredeyse homojen yayınmış denebilecek oranda Cu'ca zengin çökelti fazların oluştuğu görülmektedir. Ayrıca bu fazların yoğun olduğu bölgede sıvı faz kaynaklı gözenek oluşumu da dikkat çekicidir.



a) 500°C'de sinterlenmiş b) 640°C'de sinterlenmiş

Şekil 3. 500°C ve 640°C sıcaklıklarda sinterlenmiş TM numunelerin SEM görüntüleri

Şekil 4'de ise 500°C'de sinterlenmiş TM numunenin SEM görüntüsü ve EDS analiz sonuçları verilmiştir. Şekil 4a'daki SEM fotoğrafında yaklaşık 20 -25 µm boyutlarında Cu'ca zengin fazın yanında yer yer çevresinde çok daha küçük çökelti fazları görülmektedir. İri parçacık EDS analizinde %50 civarında Cu ve %44 civarında ise Al içerdiği görülmektedir (Şekil 4b). Diğer küçük boyutlu çöketi fazların ise %15 civarında Cu içerdiği görülmektedir. Diğer taraftan Al matrisin Cu içeriğinin %2,7 oranında olduğu 3 numaralı EDS analizinden anlaşılmaktadır. Bu sonuçlar değerlendirildiğinde, %4,5 Cu içeren Al alaşımının bu sıcaklıkta sağlanamadığı söylenebilir. Gerek sinterleme süresi ve gerekse sıcaklığı bakımından yeterli olmadığı görülmektedir.



a) 500°C'de sinterlenmiş b) EDS analiz sonuçları

Şekil 4. 500°C'de sinterlenmiş TM numunenin SEM görüntüsü ve EDS analiz sonuçları

Şekil 3b'de verilen 640 °C sıcaklıklarda sinterlenmiş TM malzeme SEM görüntüsünde ise iri Cu'ca zengin parçacıklar bulunmasa dahi çok daha küçük boyutlardaki çökelti fazların varlığı gösterilmiştir. Ancak bu sıcaklıkta oluşan aşırı sıvı faz, makro boyuta dahi TM malzemenin biçimini bozduğu için bu karışım için uygun sinter sıcaklığı olmadığını göstermektedir.

4. SONUÇ

Bu deneysel çalışma bulgularına göre aşağıdaki sonuçlar özetlenebilir;

- Yapılan yoğunluk ölçümlerinde sıkıştırma basıncının artmasıyla, yoğunluğun arttığı ve gözenekliliğin azaldığı, ancak 400 MPa'dan sonra artan sıkıştırma basıncının ham yoğunluğa etkisinin olmadığı belirlenmiştir.

- En düşük sinterleme sıcaklığı olan 500°C'de katı hal sinterlenmesi gerçekleşmiş ancak, bakır parçacıkları neredeyse başlangıçtaki yapısını korumuştur. Bununla birlikte kısmi olarak Cu'ca zengin çökeltilerde meydana gelmiştir. Fakat al matriste Cu segregasyonu çok yoğundur ve bakırın alüminyuma difüzyonu yetersiz kalmıştır.

- 570°C sinterleme işlemi ile mikroyapıda daha küçük çökeltiler şeklinde bakırca zengin fazlar görülmekle gözenek yoğunluğunda azalma belirlenmiştir. Bu sıcaklıkta sinterlenen numunelerde belirgin bir sıvı faz oluşumuna rastlanmamış ve TM numuneler fiziksel bütünlüğünü korumuştur.

- En yüksek sıcaklık olan 640°C'deki sinterleme işleminde ise yer yer Al-Cu konsantrasyon farklılıkları nedeniyle oluşan ötektik oran sebebiyle TM malzeme içinde sıvı fazların oluştuğu görülmüştür. Mikroyapıda yaygın olarak küçük boyutlardaki çökelti fazların varlığı belirlenmiştir. Ancak bu sıcaklıkta oluşan aşırı sıvı faz, makro boyuta dahi TM malzemenin fiziksel bütünlüğünü bozmuştur.

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ÖN ALAŞIM VE KARIŞIMLI ALUMIX 123 TOZU İLE ÜRETİLEN TM PARÇALARIN MEKANİK ÖZELLİKLERİNE SIKIŞTIRMA BASINCI VE SİNTER SICAKLIKLARININ ETKİSİ

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ÖZET

Toz metalurjisi (TM) ürünü sinter parçalar ve TM yöntemiyle üretilen metal matrisli kompozit (MMKp) malzemeler havacılık, savunma sanayii ve otomotiv endüstrisinde yaygın olarak kullanılan mühendislik ürünleridir. Bu malzemelerin üretiminde özgül dayanımlarının yüksek olması sebebiyle Aluminyum alaşımı tozların da yaygın kullanımı mevcuttur. TM parçaların üretiminde genellikle ön alaşımlı Al esaslı tozlar tercih edilirken kısmen ön karışımlı tozlarında kullanımı mevcuttur. Çünkü, TM ile alüminyum alaşımlarının üretimi, elementel alüminyum tozu, alaşım katkı tozları ve yağlayıcı tozdan oluşan bir toz ön karışımıyla başlar. Zira, alüminyum alaşımlarının mekanik özellikleri, bazı alaşım elementlerinin mikro veya makro ölçekte küçük ilaveleriyle geliştirilebilir. Ticari Alumix 123 tozunun üretimi ve piyasaya arz sürecinde Al esaslı AlSiMg içerikli ön alaşımlı metal tozları ile birlikte, %4,5Cu içeriği ile ön karışımlı toz olarak hazırlanır. Bu durum ise, gerek sinterleme veya gerekse sıcak presleme sürecinde Al%4,5Cu alaşımının homojen dağılımlı sağlanmasında problemler oluşturabilir. Bu çalışmada, Ticari Alumix 123 tozunun 300, 400 ve 500 MPa sıkıştırma basınçlarında soğuk preslenmesi sonrası 500, 570 ve 640 °C sıcaklıklarda bir saat süre ile sinterlenmesi ile üretilen TM parçaların mikroyapısı ve özellikle mekanik özellikleri incelenmiştir. Sinter sıcaklıklarının üretilen TM malzemelerin sertliklerine etkileri belirlenmiştir. ASTM B528-16(2020) standardına göre hazırlanan TM numunelere uygulanan testlerle çapraz kırılma dayanımları (ÇKD) belirlenmiştir. Elde edilen sonuçlar göstermiştir ki, artan sıkıştırma basıncı ve sinter sıcaklıkları ile birlikte üretilen TM malzemelerin ham ve sinter yoğunlukları artarken sertlikleri de artmaktadır. Bununla birlikte, yüksek sıkıştırma basınçlarında ve fakat düşük sinterleme sıcaklıklarındaki TM malzemelerin ÇKD değerleri önemli ölçüde düşmüştür. Ayrıca, 570 °C'de sinterlenen fakat 300 MPa ile 500 MPa'da preslenmiş malzemelerin ÇKD değerlerinde belirgin bir fark görülmemiştir. 640 °C'de sinterleme sürecinde oluşan sıvı faz sebebiyle TM malzemelerde fiziksel deformasyon meydana gelmiştir.

Anahtar kelimeler: Toz Metalurjisi, Alumix 123, Sinterleme sıcaklığı, Sertlik, Çapraz Kırılma Dayanımı

THE EFFECT OF COMPACTION PRESSURE AND SINTERING TEMPERATURES ON THE MECHANICAL PROPERTIES OF TM PARTS PRODUCED WITH PRE-ALLOYED AND MIXED ALUMIX 123 POWDER

ABSTRACT

Sintered parts produced by powder metallurgy (PM) and metal matrix composite (MMCp) materials produced by the PM method are widely used engineering products in the aerospace, defense, and automotive industries. Aluminum alloy powders are also widely used in the production of these materials due to their high specific strength. While prealloyed Al-based powders are generally preferred in the production of PM parts, premixed powders are also used to some extent. This is because the production of aluminum alloys using PM begins with a powder premix consisting of elemental aluminum powder, alloy additive powders, and lubricant powder. The mechanical properties of aluminum alloys can be improved with small additions of certain alloying elements at the micro or macro scale. During the production and marketing of commercial Alumix 123 powder, it is prepared as a premixed powder with a 4.5% Cu content, along with Al-based AlSiMg-containing prealloyed metal powders. This can create problems in ensuring a homogeneous distribution of the Al4.5% Cu alloy during both sintering and hot pressing. In this study, the microstructure and especially the mechanical properties of PM parts produced by cold pressing commercial Alumix 123 powder at compression pressures of 300, 400 and 500 MPa and then sintering at temperatures of 500, 570 and 640 °C for one hour were investigated. The effects of sinter temperatures on the hardness of the produced TM materials were determined. Transverse rupture strength (TRS) was determined by tests applied to PM samples prepared according to ASTM B528-16(2020). The results obtained showed that with increasing compression pressure and sinter temperatures, the green and sinter densities of the produced PM materials increased, while their hardness also increased. However, the TRS values of PM materials at high compression pressures but low sintering temperatures decreased significantly. In addition, no significant difference was observed in the TRS values of materials sintered at 570 °C but compressed at 300 MPa and 500 MPa. Physical deformation occurred in the PM materials due to the liquid phase formed during the sintering process at 640°C.

Keywords: Powder Metallurgy, Alumix 123, Sintering Temperature, Hardness, Transverse Rupture Strength

1.GİRİŞ

Alüminyum alaşımları günümüzde çelikten sonra en çok kullanılan metalik mühendislik malzemeleridir [1]. Düşük yoğunluk (2,7 gr/cm3), yüksek korozyon dayanımı, yüksek elektriksel iletkenlik ve diğer mühendislik malzemelerine göre yüksek spesfik dayanım gibi özellikleri sebebiyle alüminyum alaşımlarına ilgi yüksektir. Alüminyum alaşımlarının günümüzde daha çok ilgi görmesinin başka bir sebebi ise taşımacılık sektöründe yaşanan gelişmelerdir. Özellikle otomotiv ve havacılık endüstrisinde daha hafif, dolayısıyla daha az yakıt tüketen ve çevreye daha az zarar veren araçlar üretimi konusunda çalışmalar artmıştır. Daha hafif araçlar üretmek için günümüzde tercih edilen malzemelerden biri de özgül dayanımı yüksek olan alüminyum alaşımlarıdır [2, 3]. Toz metalurjisi (TM), hassas ve karmaşık parçaların uygun maliyetli ve sürdürülebilir bir şekilde seri üretimi için kullanılabilen çeşitli bir üretim tekniğidir. Döküm veya şekillendirme gibi geleneksel metal işleme yöntemleriyle büyük miktarlarda küçük ve karmaşık bileşen üretmek, genellikle pahalı ve israfa yol açan ikincil işleme operasyonları gerektirir. Bazı durumlarda, çok az veya hiç ikincil işleme operasyonu gerektirmeyen net veya net şekle yakın bileşenler üretmek için geleneksel metal işleme yöntemleri yerine TM kullanmak daha uygundur [4]. TM ile alüminyum alaşımlarının üretimi, ana matriste alüminyum tozu, alaşım katkı tozları ve yağlayıcı tozdan oluşan bir toz ön karışımıyla başlar [5]. Ön karışım, ham mukavemetli malzeme oluşturmak için tek eksenli kalıp sıkıştırmasına tabi tutulur ve ardından sinterlenir. Alumix 123 ticari alaşımdaki metal tozu, Al2014'e dayalı, alüminyum-bakır esaslı olan ilave olarak kısmen magnezyum-silisyum içeren alaşımdır [6]. Bu alaşım sistemi, ASTM Standardı B595'te belirtilen 'AC-2014' tanımıyla standartlaştırılmış olup, şu anda ticari olarak 'Alumix 123' ticari adı altında sunulmaktadır [7]. Fakat bu alaşım AlSiMg ön alaşımlı toza sonradan ilave edilen ve ağırlıkça %4,5 Cu içeren aynı zamanda ön karışımlı toz niteliğindedir. Bu durum ise uygun sintersıcaklığı, süresi veya sıkıştırma basıncı kullanılmadığı sürece önemli oranda Cu segregasyonlarına, homojen olmayan çökelti dağlımına ve dolayısıyal TM ürünün mekanik özelliklerinde önemli problemlere sebep olabilmektedir.

Bu çalışmada, TM yöntemiyle Alumix 123 tozundan üretilen toz metal numunelerde uygulanan presleme basıncı ve sinterleme sıcaklığının malzemenin yoğunluk, mikroyapı ve mekanik özellikleri üzerindeki etkilerini incelenmiştir.

2. MALZEME VE METOT

2.1 Malzeme

Deneysel çalışmalarda Alumix 123 tozu kullanılmıştır**. Alumix 123**, atomizasyonla üretilmiş alüminyum esaslı metal tozları ile elektroliz yöntemiyle elde edilmiş elektrolitik bakır tozlarının belirli oranlarda karıştırılmasıyla oluşturulan bir toz metalurjisi alaşımıdır. İçeriğinde Al–Cu–Mg–Si elementleri bulunmaktadır. Kullanılan Alumix 123 tozunun kimyasal bileşimi Tablo 1'de yer almaktadır.

Tablo 1. Alumix 123'ün kimyasal bileşimi

Element	Al	Cu	Mg	Si	Diğer
Ağırlıkça %	94.3	4.5	0.5	0.6	0.1

2.2. Deneysel Metot

Ham mukavemetli numuneler, ASTM B528-16(2020) standardında belirtilen boyutlarda ve hacimde şekillendirebilecek kalıp içerisine 7.8 gr Alumix 123 tozunun doldurularak

sıkıştırılmasıyla oluşturulmuştur. Alüminyum tozlarının sertlikleri düşük olduğu için tek eksenli presleme ile kolaylıkla yüksek yoğunluk değerlerine ulaşılabilmektedir [8]. Instron 8503 Tek Eksenli Hidrolik Pres vasıtasıyla soğuk presleme işlemi yapılmıştır. Malzemeler 3 farklı gruba ayrılıp sırasıyla 300MPa, 400MPa ve 500MPa basınç altında preslenmiştir. Farklı basınçlarda preslenmiş bu numunelerin basınç farkına göre oluşan ham yoğunluk boyutları Tablo 2'de verilmiştir.

Tablo 2. Sıkıştırma basıncına göre değişen TM ham numune boyutları

Basınç(MPa)	300MPa	400MPa	500MPa
Yükseklik (mm)	7.80	7.75	7.60
Genişlik (mm)	12.88		
Boy (mm)	31.2		

Üç farklı basınç altında preslemenin sebebi presleme basıncının malzemede meydana getirdiği mekanik özellik farklarını gözlemlemektir. Presleme işlemi oda sıcaklığında gerçekleşmiştir. Sıkıştırma işleminde kullanılan kalıbı yağlamak için çinko stearat ve alkol karışımı kullanılmıştır. Presleme işlemi sonrası numunelerin ham yoğunluğu ölçülmüştür ve ardından sinterleme işlemine geçilmiştir.

Sinterleme işlemi, toz parçacıkların birbirine bağlanmasını sağlayan, böylece dayanımlarını artıran, yüzey alanlarını düşüren bir ısıl süreçtir [9]. Sinterleme işlemiyle malzemeye sertlik ve mukavemet kazandırılmış, toz partikülleri arasındaki difüzyonu artırarak mekanik özelliklerin gelişmesi sağlanmıştır. Üç farklı basınç altında preslenen numunelerin her biri sırasıyla 500°C, 570°C ve 640°C'de 10°C /dk ısıtma hızıyla, 60dk sinterlenmiş ardından fırın ortamında yavaş soğumaya bırakılmıştır. Sinterleme işlemi Protherm marka sinter fırını yardımıyla yapılmıştır. Alüminyum tozları hangi yöntemle üretilirse üretilsin, açık atmosfer ortamında oksijene olan yüksek afinitesi sebebiyle hızla oksitlenen bir metaldir. Bu durum ise sinterlemeyi ve dolayısıyla TM malzemenin dayanımını olumsuz etkiler [10]. Sinterleme sırasında oksitlenmeyi ve korozyonu önlemek amacıyla numuneler alüminyum folyo ile kaplanmış, folyoların üzerine ise oksijen tutucu olarak titanyum parçacıkları yerleştirilmiş ve fırın ortamı argon gazı altında tutulmuştur.

Arşimet Prensibi yöntemiyle Weightlab WSA-224T analitik terazi yardımıyla yoğunluk ölçümü yapılmıştır. Arından presleme basıncı ve sinterleme sıcaklığının malzemenin kırılmaya karşı gösterdiği direnç üzerindeki etkisini incelemek amacıyla INSTRON 3400 Serisi Üniversal Çekme Dayanım Test Cihazı yardımıyla numunelere Çapraz Kırılma Dayanım (ÇKD) testi yapılmıştır. Bu test ASTM B528-16 (2020) standardına göre yapılmıştır.

Bu işlem sonrasında malzemelerin mikroyapısı Nikon Eclipse E100 cihazı yardımıyla optik mikroskop altında incelenmiştir. Bu amaçla, alüminyum ve alaşımı malzemelerde tercih edilen Keller's Reaktfi dağlayıcı ile numuneler 15 saniye dağlanmıştır. Keller's Reaktifini elde etmek için 2,5 ml HNO_3 (nitrik asit) 1,5 ml HCl (hidroklorik asit), 1,0 ml HF (hidroflorik asit) ve 95 ml saf su kullanılmıştır.

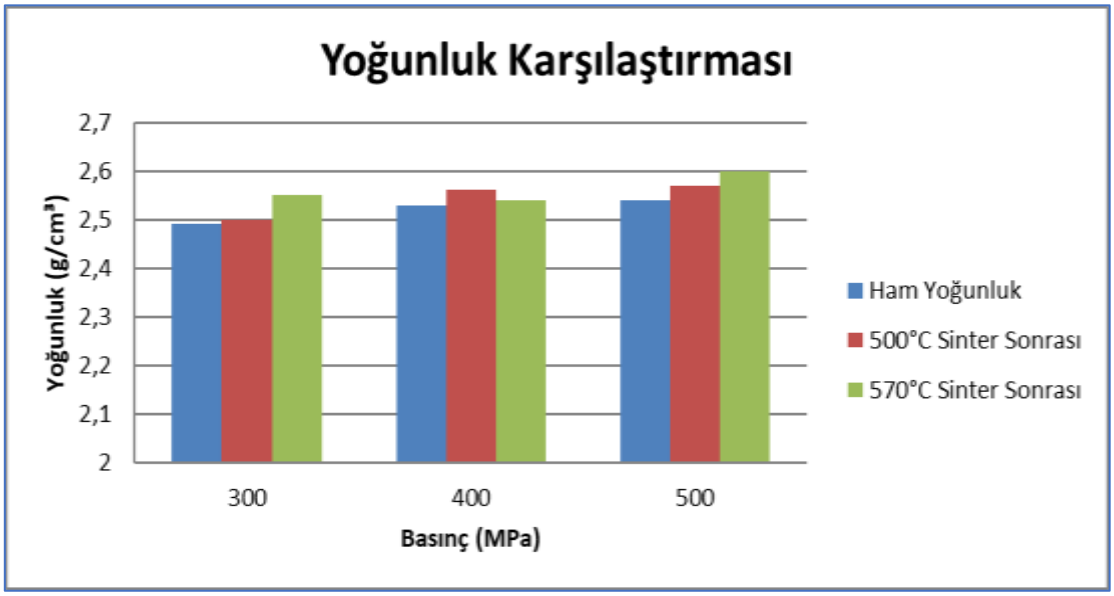
Ardından sinter sıcaklığının malzemenin sertliğine etkisini belirlemek için yalnızca 500 MPa basınç altında soğuk preslenen numuneler kullanılmıştır. Bu numuneler sırasıyla 500°C, 570°C ve 640°C'de sinterlenmiş olan üç farklı numuneye Duravision 2000 Emco Test Sertlik Cihazı yardımıyla Brinell Sertlik testi uygulanmıştır. Her üç numune yüzeyinde 3 farklı bölgeden 31.25 kgf yük uygulanmıştır ve bu yük altında malzemelerin sertliği ölçülmüştür.

3. DENEYSEL BULGULAR VE TARTIŞMA

3.1 Sıkıştırma Basıncı ve Sinterleme Sıcaklığının Yoğunluğa Etkisi

Şekil 1'de görüldüğü üzere uygulanan presleme basıncının artmasıyla ham yoğunluğun ve sinterleme sonrası ölçülen yoğunluğun arttığı görülmektedir. Artan presleme basıncı ile toz taneleri arasındaki boşluklar kapanır, parçacıklar arası mekanik girişim artar. Buradan yola çıkarak presleme basıncının artmasının yoğunluğu da arttırdığını söylenebilir.

Sinter işlemi sonrasında malzemelerin yoğunluklarının ham yoğunluklarından fazla olduğu görülmektedir. Her sıcaklıktaki sinterleme işlemi yoğunluk artışı sağlamıştır. Sinter sonrası en yoğun malzemenin 500MPa basınç altında preslenmiş ve 570°Cde sinterlenmiş malzeme olduğu görülmektedir. Sinter sıcaklığı arttığında malzeme yoğunluğu da buna bağlı olarak artar. Sinterleme sıcaklık yükseldikçe katı hal difüzyonu artar gözenekler küçülür ve taneler birbirine daha yoğun bağlanır. Presleme basıncın artması her zaman yoğunluğu artırmaz. Özellikle aşırı yüksek presleme basıncından sonra ham yoğunlukta düşme gözlemlenebilir. Buna geri yaylanma sebep olmaktadır [11].



Şekil 1. Sıkıştırma basıncı ve sinterleme sıcaklıklarının TM numune yoğunluklarına etkisi

3.2 Sıkıştırma Basıncı ve Sinterleme Sıcaklığının Mikroyapıya Etkisi

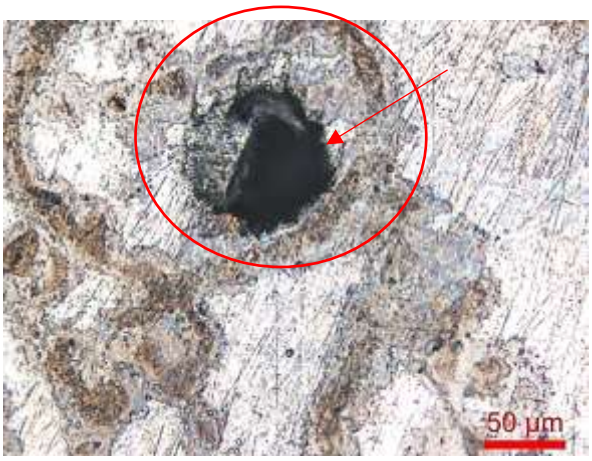
Şekil 2'de 500 MPa'da preslenen TM numunelerin üç farklı sıcaklıkta sinterlendikten sonraki mikroyapıları verilmiştir. Şekil 3a'daki en düşük sinterleme sıcaklığında halen iri Cu parçacıklarının varlığı görülmektedir. Bu sıcaklığın Cu↔Al yayınımı için yeter sıcaklık olmadığı görülmektedir. Ayrıca, bu malzemede tane sınırlarında sinterleme yetersizliği ve kısmi gözenekler mevcuttur (okla gösterildi). Cu'ca zengin parçacıklar ve bölgeler çember içinde gösterilmiştir. 570°C'de sinterlenmiş malzemede ise sinterleşmenin çok daha iyi olduğu görülmektedir. Bununla birlikte halen Cu'ca zengin parçacıkların yoğunluğu dikkat çekicidir. Özellikle tane sınırlarını takip eden dağılımda açık renk tonlamadaki fazın sinter sırasında ötektik oranda Al-Cu alaşımı ile oluşan sıvı fazın (ötektik sıvı sıcaklığı 548 °C) olabileceği ihtimali de değerlendirilmelidir (Şekil 2b). Şekil 2c'de 640 °C'de sinterlenmiş malzemenin mikroyapısı görülmektedir. Burada oluşan 70-80 µm çapındaki gözeneğin sıvı faz nedenli olduğu gayet açıktır. Gözenek çevresinde oluşmuş Cu'ca zengin halkanın merkezine doğru ötektik Al-Cu alaşım oranın sıvı faza sebep olduğu söylenebilir.



a) 500 °C'de sinterlenmiş malzeme



b) 570 °C'de sinterlenmiş malzeme

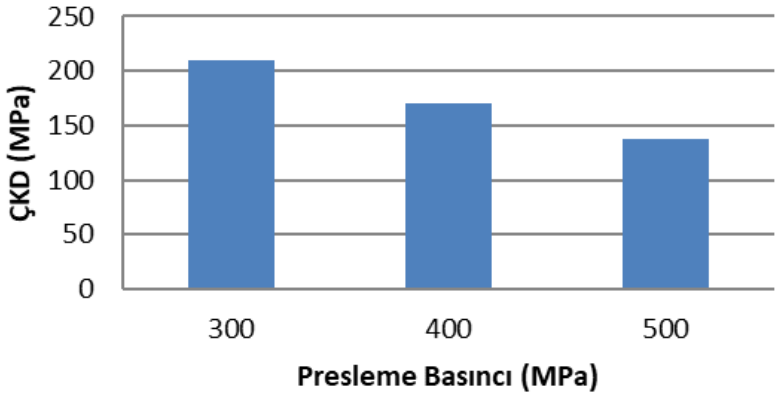


c) 640 °C'de sinterlenmiş malzemenin

Şekil 2. Sinterleme sıcaklığının mikroyapıya etkisi

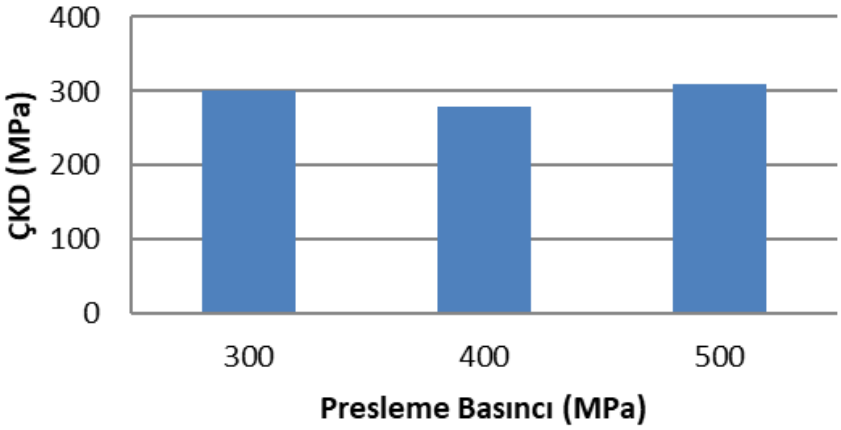
3.3 Sıkıştırma Basıncı ve Sinterleme Sıcaklığının ÇKD'ye Etkisi

Şekil 3'de 500 °C'de sinterlenmiş malzemelerin Çapraz Kırılma Dayanımı (ÇKD) görülmektedir. 300MPa basınç altında sinterlenmiş numunenin ÇKD'si 210MPa , 400'de 170MPa ve 500'de 137 MPa olduğu görülmektedir. Şekilde 300MPa basınçla preslenmiş malzemenin en yüksek dayanıma sahip olduğu görülüyor. Ancak 500 MPa basınçtaki ÇKD değeri çok daha düşüktür. Genel olarak basıncın artması ile birlikte kırılma dayanımının artması beklenirken burada düştüğü görülmektedir. Yüksek presleme basıncı parçacıklar arası boşlukları kapalı gözenekler haline getirebilir. Kapalı gözenekler de sinterleme sırasında gaz çıkışını engeller ve bunun sonucunda presleme doğrultusuna dik (radyal yönde) parallel çatlaklar meydana getirebilir. Bu durum özellikle düşük sinterleme sıcaklıklarındaki zayıf sinterleşme sebebiyle de dayanımı düşüren bir etken olabilir. Bunu yanında, yüksek sıkıştırma basıncı sonrası ve kalıptan çıkış sırasındaki geri yaylanmanın oluşturabileceği radial çatlakların düşük sinter sıcaklıklarında benzer etkileri göstermesi muhtemeldir. Bu alaşım için bu sinter süresi ve sıcaklığında uygun presleme basıncının 300 MPa olacağı söylenebilir.



Şekil 3. 500 °C'de sinterlenmiş malzemelerin presleme basıncına göre ÇKD değerleri

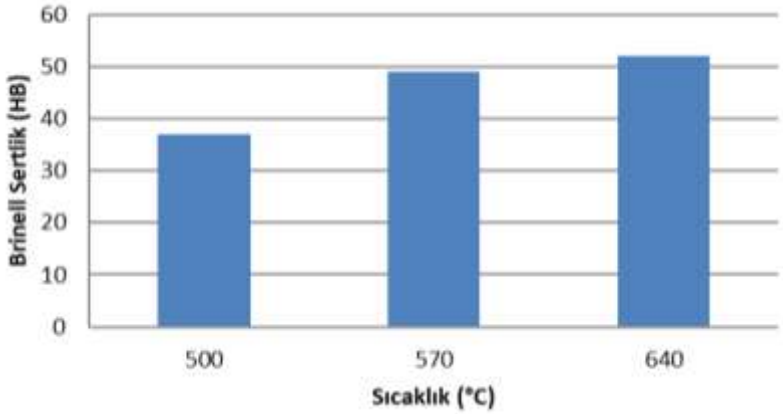
Şekil 4 incelendiğinde ise sinter sıcaklığının artmasıyla beraber her sıkıştırma basıncı için kırılma dayanımının önemli miktarda arttığı görülmüştür. 300MPa basınçla sinterlenen numunenin ÇKD değeri 300 MPa , 400'de 280 MPa ve 500'de ise 310 MPa olmuştur. Bu sonuçlar, artan sinterleme sıcaklığı ile birlikte önemli miktarda sinterleşmenin gerçekleştiğini ve TM malzemelerin dayanımlarının da arttığını göstermektedir. Bununla birlikte 300 ve 500 MPa'da preslenen numunelerin ÇKD değerlerinin çok yakın olması da dikkat çekicidir.



Şekil 4. 570 °C'de sinterlenmiş malzemelerin presleme basıncına göre ÇKD değerleri

3.4 Sinterleme Sıcaklığının TM Malzeme Sertliğine Etkisi

Şekil 5 incelendiğinde 500MPa basınçta preslenmiş malzemelerin artan sinterleme sıcaklıklarına bağlı olarak sertliklerinde de artış gözlenmiştir. 500°C'de sinterlenen malzemenin ortalama sertliği 38 HB_W ölçülürken 570°C'de 49HB_W ve 640°C'de 52HB_W ölçülmüştür. Bu durum, TM numunelerin artan sinter sıcaklığı ile birlikte sinterleşme oranının ve yoğunluğun artmasının yanında, Al matriste Cu difüzyonunun artması ile alaşımla oranının artmasına bağlanabilir. Ancak 640 °C'de oluşan sıvı faz sebebiyle, TM numune dışında katılaşan Cu'ca zengin ötektik karışım genel olarak malzeme hacminde Cu kaybına ve gözenekliliğe sebep olmuştur. Bu durum, belirtilen sıcaklıkta yeterli sertlik artışının görülmemesine neden olabilir.



Şekil 5. Sinterleme Sıcaklığının TM Malzeme Sertliğine Etkisi

4. SONUÇ

Bu çalışmanın amacı kapsamında yapılan deneysel çalışmalar sonucunda aşağıdaki sonuçlar özetlenebilir;

500MPa basınç altında preslenen malzemelerin mikroyapısı incelendiğinde 500 °C'de sinterlenen malzemenin mikroyapısında yeter yayınım sıcaklığı olmamasından dolayı iri Cu parçacıklarının varlığı gözlemlenmiştir.Aynı zamanda kısmi gözenekler de mevcuttur. 570 °C'de sinterlenen malzemede ise sinterleşmenin çok iyi olduğu ama hala Cu'ca zengin parçacıkların da olduğu gözlemlenmiştir. 640 °C'de ise ötektik Al-Cu alaşım oranının sıvı faza sebep olduğu söylenebilir.

Yapılan çalışmalar sonucunda, presleme basıncı arttıkça numunelerin sinter öncesi yoğunluklarının (ham yoğunluk) arttığı, sinter işlemi sonrasında ise malzemenin yoğunluklarının ham yoğunluklarından fazla olduğu gözlemlenmiştir. Her sıcaklıktaki sinterleme işlemi sonrasında yoğunluğun arttığı gözlemlenmiştir. Sinter sonrası en yoğun malzeme 500MPa basınç altında sıkıştırılmış 570 °C'de sinterlenmiş malzemedir. Sinter sıcaklığı artışıyla doğru orantılı olarak yoğunluk da artar.

Çapraz Kırma Dayanım testinde 500 °C'de sinterlenmiş malzemelerde 300MPa basınçla preslenmiş malzemenin en yüksek dayanıma sahip olduğu görülüyor (210MPa). Bu alaşım için bu sinter süresi ve sıcaklığında uygun presleme basıncının 300 MPa olacağı söylenebilir.

570 °C'de sinterlenmiş malzemelere bakıldığında ise sinter sıcaklığının artmasıyla beraber her sıkıştırma basıncı için kırılma dayanımının önemli miktarda arttığı görülmüştür. En yüksek dayanım 500 Mpa basınç altında preslenip 570 °C'de sinterlenmiş malzemede gözlemlenmiştir (310MPa).

Brinell sertlik testinde 500 MPa'da preslenen TM numunelerin sertliği, sinterleme sıcaklığının 500°C'den 640°C'ye artmasıyla 38 HBW'den 52 HBW'ye yükselmiştir. Sertlik artışı, sinterleşme ve yoğunluğun gelişmesinin yanı sıra Al matristeki Cu difüzyonunun artmasına bağlanmıştır. Ancak 640°C'de oluşan sıvı faz nedeniyle Cu kaybı ve gözeneklilik meydana geldiğinden, bu sıcaklıkta sertlik artışı sınırlı kalmıştır. Sertliği en yüksek malzemenin 570MPa basınçta preslenip 640°C'de sinterlenen malzeme olduğu görülmüştür (52 HBW).

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ACI BAKLA (LUPINUS ALBUS) İLAVESININ KIRMIZI ET KÖFTESININ FIZIKSEL, MIKROBIYOLOJIK VE DUYUSAL ÖZELLIKLERI ÜZERINE ETKISI

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ÖZET

Et ürünleri, yüksek protein içeriğiyle beslenmede önemli bir yere sahiptir. Bununla birlikte, hayvansal protein kaynaklarının sürdürülebilirliği ve maliyeti, bitkisel protein alternatiflerinin kullanımını arttırmaktadır. Acı bakla (*Lupinus albus*) yüksek oranda protein, lif ve biyoaktif bileşikler içeren bir baklagildir. Son yıllarda, acı bakla unu gıda endüstrisinde fonksiyonel bileşen olarak kullanılmaktadır. Bu çalışmada, kırmızı et köftesine farklı oranlarda (%10, %20 ve %30) acı bakla (Lupinus albus) ilave edilerek deneysel köfte örnekleri hazırlanmıştır. Deneysel köfte örneklerinin, fiziksel (ağırlık kaybı, çap küçülmesi), renk analizleri (L, a ve b değeri), mikrobiyolojik (toplam mezofil aerob genel canlı sayısı, koliform bakteri sayısı ve maya-küf sayısı) ve duyusal özellikleri incelenmiştir. Acı bakla, ortalama 60 dakika haşlanarak kabukları soyulmuş ve blenderda öğütülerek hamur haline getirilmiştir. Et ağırlığı esas alınarak farklı oranlarda acı bakla ilave edilen et köftelerine % 2 oranında tuz ilave edilmiştir. Köfteler airfryer'da 180 °C'de 5 dakika pişirilmiş ve pişirme süresince termal kamera ile sıcaklık dağılımları kaydedilmiştir. Artan bakla oranı ile köftelerde ağırlık kaybının arttığı ve çapın küçüldüğü belirlenmiştir. Renk analizinde L* (açıklık), a* (kırmızılık) ve b* (sarılık) değerlerinde önemli farklılıklar gözlenmiştir. Acı bakla unu miktarı arttıkça L değeri yükselmiştir. Mikrobiyolojik analizlerde koliform bakteri tespit edilebilir düzeyin altında (<10 log kob/g) tespit edilmiştir. Maya-küf sayısı 1.1 $\log_{10}$ kob/g, toplam aerob mezofil genel canlı sayısı ise 1.8 $\log_{10}$ kob/g olarak belirlenmiştir. Sekiz kişilik panel ile yapılan duyusal analizlerde, %10 bakla unu içeren köftelerin renk, aroma ve genel beğeni açısından en yüksek puanları aldığı saptanmıştır. Sonuç olarak, acı bakla unu et köftesi üretiminde bitkisel protein katkısı olarak değerlendirilebilir; ancak yüksek oranların ürünün duyusal özelliklerini olumsuz etkilediğini söylemek mümkündür.

Anahtar kelimeler: Acı bakla unu, köfte, airfryer, termal görüntüleme, duyusal analiz, mikrobiyoloji, renk ölçümü.

THE EFFECT OF BITTER LUPIN (LUPINUS ALBUS) ADDITION ON THE PHYSICAL, MICROBIOLOGICAL AND SENSORY PROPERTIES OF BEEF MEATBALLS

ABSTRACT

Meat products have an important place in human nutrition due to their high protein content. However, increasing concerns about the sustainability and cost of animal-based protein sources have promoted the use of plant-based protein alternatives. Bitter lupin (*Lupinus albus*) is a legume rich in protein, fiber, and bioactive compounds. In recent years, lupin flour has been used as a functional ingredient in the food industry. In this study, beef meatballs were prepared by adding bitter lupin (Lupinus albus) at different levels (10%, 20%, and 30%). The experimental meatballs were analyzed for physical properties (weight loss, diameter shrinkage), color parameters (L*, a*, b* values), microbiological characteristics (total mesophilic aerobic count, coliform count, and yeast–mold count), and sensory attributes. Bitter lupin was boiled for approximately 60 minutes, peeled, and ground into a paste using a blender. Salt (2%) was added to the meatballs containing different levels of lupin based on meat weight. The meatballs were cooked in an air fryer at 180°C for 5 minutes, and temperature distribution during cooking was monitored using a thermal camera. Results showed that increasing lupin levels led to higher weight loss and greater diameter reduction in the meatballs. Significant differences were observed in L* (lightness), a* (redness), and b* (yellowness) values; L* values increased with higher lupin content. Coliforms were below detectable levels (<10 CFU/g). Yeast–mold count was 1.1 $\log_{10}$ CFU/g, while total mesophilic aerobic count was 1.8 $\log_{10}$ CFU/g. Sensory evaluation by an eight-member panel indicated that meatballs containing 10% lupin flour received the highest scores for color, aroma, and overall acceptability. In conclusion, bitter lupin flour can be considered a plant-based protein additive in meatball production; however, higher levels may negatively affect sensory quality.

Keywords: Bitter lupin flour, meatball, air fryer, thermal imaging, sensory analysis, microbiology, color measurement.

Giriş

Et ve et ürünleri, yüksek biyolojik değerli proteinleri, esansiyel amino asitleri, vitamin ve mineralleri nedeniyle insan beslenmesinde vazgeçilmez bir konuma sahiptir (Troy ve Kerry, 2010). Ancak son zamanlarda modern gıda sistemlerinde sürdürülebilirlik, ekonomik üretim, enerji tüketimi ve çevresel etkiler gibi faktörlerin yanısıra , aynı zamanda sağlıklı beslenme alışkanlıklarına yönelik artan farkındalık ve ilgiye cevap verebilecek yeni, güvenli ve sağlıklı gıdalar geliştirme ihtiyacı nedeniyle de bitki kaynaklı besinlere ve biyoaktif bileşiklere artan bir ilgi duyulmaktadır. Bu nedenle bitkisel kaynaklı protein içerikli katkılar ve baklagiller hem maliyet avantajı hem de fonksiyonel ve teknolojik faydalar sağlaması nedeniyle et ürünlerinde yaygın olarak kullanılmaya başlanmıştır (Pintado ve Delgado-Pando, 2020; Pereira ve ark., 2022). Bu bağlamda baklagiller, zengin protein ve diyet lifi içerikleriyle özellikle kıyma bazlı ürünlerde et ikamesi veya fonksiyonel bileşen olarak değerlendirilen başlıca bitkisel kaynaklar arasındadır (Durazzo ve ark., 2015). Acı bakla tohumlarına olan ilgi, gıda hazırlamadaki esnekliği ve sağladıkları sağlık yararları hakkındaki artan bilgi birikimiyle sürekli olarak artmaktadır. Lupinus cinsinin türleri arasında, beyaz acı bakla (*Lupinus albus* L.) dikkate değer bir potansiyele sahiptir (Pereira ve ark., 2022). Fabaceae familyasından Lupinus cinsine ait, protein açısından zengin bir baklagil olan acı bakla, bu tür alternatifler için umut vadeden bir aday olarak kendini göstermektedir. Besinsel açıdan bakıldığında, beyaz acı bakla tohumları %32,9'dan %36,0'ın üzerine kadar yüksek bir protein içeriğine sahiptir. Yağ içeriği %9 ila %13 arasında değişir ve yüksek bir PUFA konsantrasyonuna sahiptir; bu da değerli bir temel yağ asidi kaynağıdır; ayrıca, diğer bitkisel yağlara kıyasla yüksek bir n3/n6 çoklu doymamış yağ asidi oranına sahiptir ve hayvan yemi için uygundur. Dahası, beyaz acı bakla, antioksidan aktiviteyi artıran ve sağlığı iyileştiren fenolik asitler, flavonlar ve izoflavonlar gibi birçok değerli biyolojik olarak aktif madde ile karakterize edilmektedir (Devkota ve ark., 2023; Gresta ve ark.,2023). Soya fasulyesinin aksine, acı baklalar olumlu çevresel etkileri, genetiği değiştirilmemiş organizma (GDO) statüsü, tripsin inhibitörlerinden ari olmaları ve genetiği değiştirilmemiş çeşitler olmaları nedeniyle sürdürülebilir ve daha sağlıklı bir seçenek olarak kabul edilmektedir. Acı bakla tohumları prebiyotik etki gösterebilen oligosakkaritler ve biyoaktif alkaloidler taşımaktadır (Dhakal ve ark., 2024; Tosoroni ve ark., 2025). Besinsel açıdan glütensiz yapıda olması ve düşük glisemik indeks göstermesi de bu baklagilin gıda formülasyonlarında tercih edilme nedenleri arasındadır (Hall et al., 2017). Son yıllarda acı bakla unu; hamur ürünleri, atıştırmalıklar, süt ürünleri ve et ürünlerinde fonksiyonel bileşen olarak yaygın şekilde kullanılmaya başlanmıştır (Duranti, 2000; Pereira ve ark., 2022). Et ürünlerinde ise su tutma kapasitesini artırma, pişme verimini iyileştirme, yağ ikamesi, tekstürel özelliklerde modülasyon sağlama gibi olumlu etkileri rapor edilmiştir (Gürsoy ve Sarıçoban, 2013).

Köfte, Türkiye başta olmak üzere birçok ülkede yaygın olarak tüketilen, kıyma bazlı bir et ürünüdür ve formülasyonunda yapılacak değişiklikler ürünün fiziksel (pişme kaybı, çap daralması, doku), kimyasal (renk, pH) ve mikrobiyolojik özellikleri üzerinde doğrudan etkili olabilmektedir (Öztürk ve Serdaroğlu, 2017). Ayrıca tüketici kabulü açısından duyusal değerlendirmeler, yeni ürün geliştirme süreçlerinde kritik bir yer tutmaktadır. Acı baklanın köfte gibi ısıl işlem gören ürünlerde davranışı, hem unun su ve yağ bağlama kapasitesi hem de protein yapısının ısıyla geçirdiği değişimlerle ilişkilidir. Literatürde lupin ununun et ürünlerinde yağ azaltımına yardımcı olduğu, ürün verimini artırdığı ve besin değerini yükselttiği bildirilmektedir (Clark ve ark., 2020). Ancak artan lupin oranı, ürün renginde açılmaya, aroma profilinde baklagil kokusunun hissedilmesine ve tekstürel değişimlere neden olabilmektedir (Belski, 2012).

Bu bağlamda, acı baklanın farklı oranlarda köfte formülasyonuna eklenmesinin ürün kalitesine etkilerinin araştırılması hem bitkisel protein kaynaklarının değerlendirilmesi hem de

sürdürülebilir et ürünleri geliştirilmesi açısından önem taşımaktadır. Aynı zamanda airfryer gibi yeni nesil pişirme ekipmanlarıyla gerçekleştirilen ısıl işlemlerin ürün üzerindeki etkilerinin incelenmesi, modern tüketim trendleriyle uyumlu yeni veri sağlamaktadır.

Bu çalışma, farklı oranlarda acı bakla (*Lupinus albus*) ilavesinin kırmızı et köftesinin fiziksel, renk, mikrobiyolojik ve duyusal özellikleri üzerine etkilerini belirlemeyi amaçlamaktadır. Elde edilen bulguların, fonksiyonel özellikleri artırılmış, bitkisel kaynaklı proteinle zenginleştirilmiş et ürünlerinin geliştirilmesine yönelik literatüre katkı sağlayacağı öngörülmektedir.

Materyal- Metot

Acı bakla Afyon' da yerel bir ticari işletmeden temin edilmiştir. Kıyma ve tuz Sivas' ta ticari bir işletmeden elde edilmiştir.

Metot

Çalışmada kullanılacak acı bakla bir gece suda bekletilmiş ve ardından ortalama 1 saat haşlanmıştır. Haşlanan acı bakla meyvelerinin kabukları soyulmuş ve ev tipi mutfak öğütücüsünden geçirilerek parçalanmıştır.

Kıyma ağırlığı üzerinden; kıyma ağırlığının % 10' u kadar ezilmiş acı bakla ilave edilen grup; % 20' si kadar ezilmiş acı bakla ilave edilen grup ve % 30' u kadar ezilmiş acı bakla ilave edilen grup olacak şekilde üç deneysel grup oluşturulmuştur (Resim 1). Deneysel grupların hepsine köfte hamuru ağırlığının %2 si kadar tuz ilave edilmiştir. Deneysel örnekler 180 C' de ortalama 5 dakika airfryda pişirilerek analizleri yapılmıştır (Resim 2).



Resim 1. Deneysel köfte örnekleri



Resim 2. Pişirilmiş deneysel köfte örnekleri

Mikrobiyolojik Analizler

Toplam Mezofil Aerob Bakteri Sayımı

Toplam mezofil aerob bakteri sayımı **ISO 4833-1:2013** standardına göre gerçekleştirilmiştir. Uygun dilüsyonlardan **1 mL**'lik örnekler steril petri kaplarına aktarılmış ve Plate Count Agar (PCA; Merck, Almanya) kullanılarak dökme-plak (pour-plate) yöntemi uygulanmıştır. Plaklar **30 ± 1 °C'de 72 saat** inkübe edilmiştir.

Koliform Bakteri Sayımı

Koliform bakteri sayımı **ISO 4832:2006** standardına göre yapılmıştır. Uygun dilüsyonlardan **0,1 mL** alınarak Violet Red Bile Agar (VRBA; Merck, Almanya) dökme plak yöntemi ile inoküle edilmiştir. Plaklar **37 ± 1 °C'de 24 saat** inkübe edilmiştir. Tipik koyu kırmızı renkli koloniler koliform olarak değerlendirilmiştir.

Maya ve Küf Sayımı

Maya ve küf sayımı **ISO 21527-1:2008** standardına göre yapılmıştır. Uygun dilüsyonlardan **0,1 mL** alınarak Patato Dekstroz Agar (PDA; Merck, Almanya) üzerine dökme plak yöntemiyle inoküle edilmiştir. Plaklar **25 ± 1 °C'de 5–7 gün** inkübe edilmiştir.

Fiziksel Analizler

Ağırlık Kaybı (Pişirme Kaybı)

Ağırlık kaybı, pişirme öncesi ve sonrası ağırlık farkına dayalı olarak hesaplanmıştır. Her bir köfte örneği pişirme öncesinde dijital terazi (±0.01 g hassasiyetli; Sartorius, Almanya) kullanılarak tartılmıştır. Köfteler airfryer'da 180 °C'de 5 dakika pişirildikten sonra oda sıcaklığında 10 dakika dinlendirilmiş ve tekrar tartılmıştır. Metot literatürde bildirilen standart yaklaşıma göre uygulanmıştır (Serdaroğlu ve Denizer, 2005; Aleson-Carbonell ve ark., 2005).

Çap Ölçümü (Çap Büzülmesi)

Çap ölçümleri, pişme sırasında oluşan şekil değişikliklerinin belirlenmesi amacıyla gerçekleştirilmiştir. Pişirme öncesi ve sonrası köftelerin çapı, paslanmaz çelik dijital kumpas (Mitutoyo, Japonya) kullanılarak iki farklı eksenden ölçülmüş ve sonuçların ortalaması alınmıştır. Bu yöntem daha önce benzer et ürünleri çalışmalarında önerilen protokole uygundur (Öztürk ve Serdaroğlu, 2015; Pietrasik ve ark., 2010).

Renk Analizi

Renk ölçümleri, CIE L*a*b* renk uzayında Minolta CR-400 (Konica Minolta, Japonya) kolorimetre kullanılarak gerçekleştirilmiştir. Cihaz ölçüm öncesi standart beyaz kalibrasyon plağı ile kalibre edilmiştir. Her bir köfte örneğinin dış yüzeyinden üç farklı noktadan ölçüm alınmış ve ortalama L* (açıklık), a* (kırmızılık) ve b* (sarılık) değerleri hesaplanmıştır. Analizler, CIE (Commission Internationale de l'Éclairage) standartlarına uygun olarak yürütülmüştür (CIE, 1986). Et ürünlerinde renk analizine ilişkin metotlar AMSA (2012) kılavuzuna göre uygulanmıştır.

Duyusal Analiz

Duyusal değerlendirme, köftelerin **renk, aroma, lezzet, kıvam, homojen görünüm ve genel beğeni** gibi organoleptik özelliklerini belirlemek amacıyla yapılmıştır. Analizler için **8 kişilik uzman panel** oluşturulmuştur. Köfteler pişirildikten sonra **oda sıcaklığında 10 dakika dinlendirilmiş** ve panelistlere kodlanmış, rasgele sırayla sunulmuştur. Panelistler her

parametreyi **5 puanlık hedonik ölçek** (1 = çok kötü, 2 = kötü, 3 = orta, 4 = iyi, 5 = çok iyi) kullanarak değerlendirmiştir (Öztürk ve Serdaroğlu, 2015).

Termal Görüntüleme

Pişirme sırasında köftelerin sıcaklık dağılımını izlemek için **termal kamera** (FLIR E8, FLIR Systems, ABD) kullanılmıştır. Köfteler **airfryer'da 180 °C'de 5 dakika** pişirilirken kamera ile yüzey sıcaklığı ve merkez sıcaklığı sürekli olarak kaydedilmiştir. Termal görüntüler, FLIR Tools yazılımı kullanılarak analiz edilmiş ve her örnek için maksimum, minimum ve ortalama sıcaklık değerleri belirlenmiştir (Pietrasik ve ark., 2010; Zhang ve ark., 2018).

İstatistiksel Analizler

Tüm veriler üç bağımsız tekrarlama üzerinden elde edilmiştir. Gruplar arası farklılıklar **Tek Yönlü Varyans Analizi (One-Way ANOVA)** ile incelenmiş ve anlamlı farklılık durumunda **Tukey HSD post-hoc testi** uygulanmıştır. Anlamlılık seviyesi **$p < 0.05$** olarak belirlenmiştir (Steel ve ark., 1997; Öztürk ve Serdaroğlu, 2015).

Bulgular

Deneysel köfte örneklerinde koliform bakteri sayısı tespit edilebilir düzeyin altında bulunmuştur (<10 log kob/g). Deneysel köfte örneklerinde tespit edilen maya-küf sayısı (MK) ve toplam mezofil aerob (TMAB) tablo 1' de verilmiştir. En düşük mikroorganizma sayısı % 10 acı bakla içeren grupda tespit edilmiştir. Ancak üç grup içinde elde edilen değerler tüketim sınırının altındadır.

Tablo 1. Deneysel köfte örnekleri mikrobiyolojik analiz bulguları

Örnekler	Mikroorganizma sayısı (log 10 kob/g)	
	MK	TMAB
% 10	1.1±0.01	1.8±0.02 ^{B}
% 20	1.3±0.01	2.3±0.01 ^{A}
% 30	1.7±0.02	2.6±0.01 ^{A}

^{A,B} :aynı süründeki farklı harfler istatistiki açıdan önemlidir ($p<0.05$)

Deneysel örneklere ait pişirilme sırasındaki iç sıcaklık değerleri ve çap değişimi ile ağırlık kaybı verileri tablo 2' de verilmiştir. Tablo 2 incelendiğinde, örneklerin %10, %20 ve %30 oranlarındaki varyantları arasında ağırlık kaybı, çap ve iç sıcaklık açısından belirgin farklılıklar gözlenmektedir. Ağırlık kaybı açısından, %10 ve %20 örnekleri istatistiksel olarak benzer (B harfi ile gösterilmiştir) değerler sergilerken, %30 örneği anlamlı derecede daha yüksek bir ağırlık kaybına sahiptir (41,95 A ± 0,00). Bu durum, örnek oranının artmasıyla ağırlık kaybının da belirgin şekilde yükseldiğini göstermektedir.

Örneklerin çap değerleri açısından, %10 örneği (60,16 A ± 0,01) istatistiksel olarak diğerlerinden farklıdır ve en büyük çap değerine sahiptir. %20 ve %30 örnekleri ise sırasıyla 51,93 B ± 0,01 ve 50,00 C ± 0,02 değerleri ile daha düşük çap göstermektedir. Bu bulgu, örnek oranının artmasıyla çapta azalma eğilimi olduğunu ortaya koymaktadır.

İç sıcaklık açısından ise %20 örneği (90 ºC) en yüksek değeri göstermekte olup, %10 ve %30 örneklerine göre daha yüksektir. Bununla birlikte, iç sıcaklık değişimi örnek oranına lineer bir şekilde bağlı görünmemektedir.

Genel olarak, örnek oranının artması ağırlık kaybını artırırken, çapı azaltmakta; iç sıcaklık ise örnek oranına göre değişkenlik göstermektedir. Bu sonuçlar, örnek bileşiminin termal ve fiziksel özellikler üzerindeki etkisini ortaya koymaktadır.

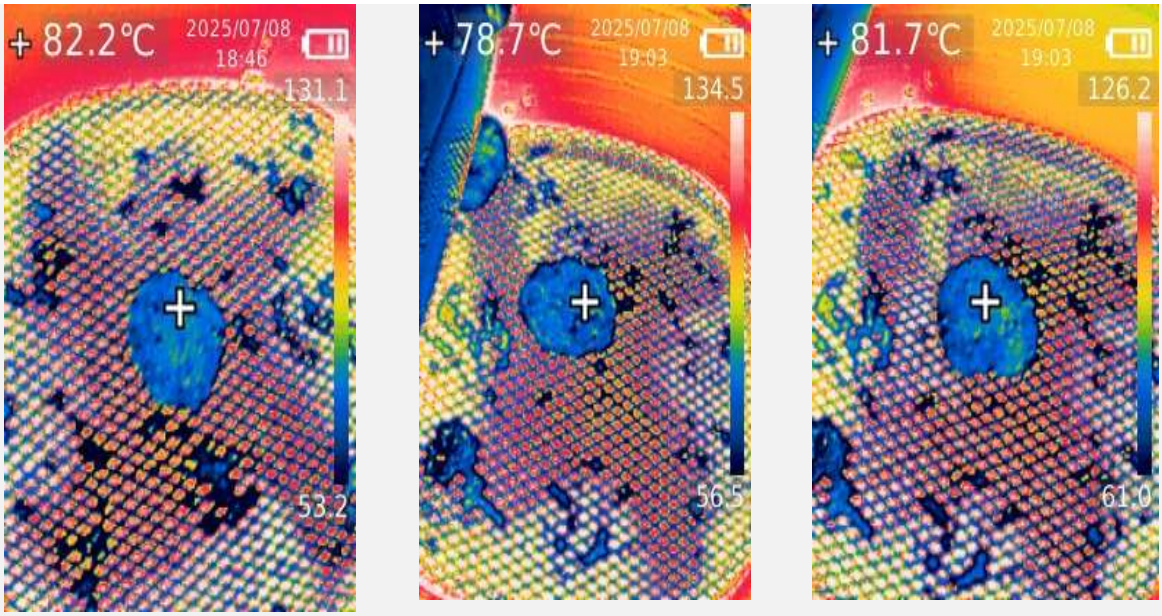
Tablo 2. Deneysel örneklerin fiziksel özellikleri ve pişirilme sırasındaki sıcaklık değişimleri

Örnekler	Ağırlık kaybı (%)	Çap (%)	İç sıcaklığı (ºC)
% 10	33,35 $^{B}\pm$ 0,01	60,16$^{A}\pm$ 0,01	86,5
% 20	36,25$^{B}\pm$ 0,05	51,93$^{B}\pm$ 0,01	90
% 30	41,95 $^{A}\pm$ 0,00	50,00$^{C}\pm$ 0,02	85,1

^{A,B} :aynı süründeki farklı harfler istatistiki açıdan önemlidir ($p<0.05$)

Deneysel köfte örneklerine ait pişirilme sırasında elde edilen termal görüntüler resim 3, resim 4 ve resim 5’ de verilmiştir.

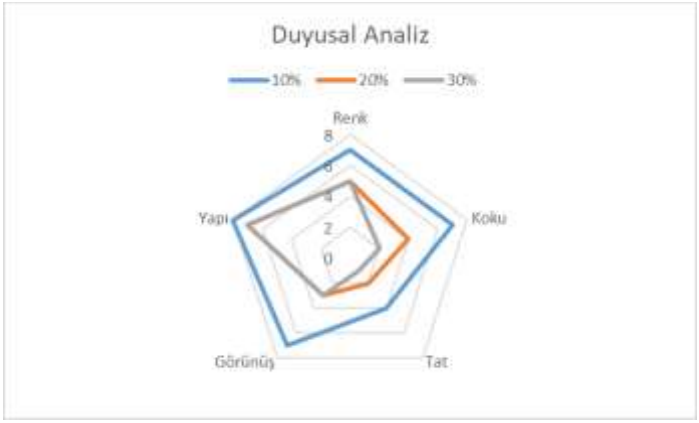




Resim 3 **Resim 4** **Resim 5**

Deneysel örneklere ait duyusal analiz bulguları grafik 1' de verilmiştir. **%10 Bakla** (mavi çizgi) tüm duyusal kriterlerde en yüksek puanları almıştır. Özellikle **yapı, görünüş** ve **renk** kriterlerinde diğer gruplara göre belirgin şekilde üstündür. Bu, düşük oranlarda acı bakla ilavesinin köfte duyusal özelliklerini olumlu etkilediğini göstermektedir**. %20 Bakla** (turuncu çizgi) orta seviyede puanlar almıştır. **Renk** ve **yapı** açısından %10'a yakın, ancak **koku** ve **tat** kriterlerinde belirgin bir düşüş gözlemlenmektedir. **%30 Bakla** (gri çizgi) en düşük puanları almıştır. Tüm kriterlerde düşüş vardır, özellikle **tat** ve **koku** değerleri ciddi şekilde azalmıştır. Bu durum, yüksek oranlarda acı bakla ilavesinin köftenin duyusal kabulünü olumsuz etkilediğini ortaya koymaktadır. Duyusal analiz sonuçları, **acı bakla ununun %10 oranında ilavesinin köfte kalitesini desteklediğini,** ancak %20–%30 oranlarının özellikle **tat ve koku** kriterlerinde olumsuz etkiler yarattığını göstermektedir. Bu sonuç, literatürde bildirilen bitkisel protein katkılarının yüksek oranlarda ürünün duyusal kabulünü düşürdüğü bulgularıyla uyumludur (Öztürk ve Serdaroğlu, 2015; Pintado ve Delgado-Pando, 2020).

Grafik 1. Deneysel örneklerin duyusal analiz sonuçları



Çiğ ve pişmiş etin rengi, özellikle tüketici satın alma tercihleri açısından en önemli kalite parametrelerinden biridir ve aynı zamanda genel et kalitesiyle de ilişkilidir (Font-i-Furnols ve Guerrero. 2014). CIE (Uluslararası Aydınlatma Komisyonu) sistemine göre L* açıklığı, a* kırmızılığı ve b* sarılığı ifade etmektedir. Tablo 3`de görüldüğü gibi acı bakla unu ilave edilen çiğ köfte örneklerinin L* ve b*değerleri acı bakla unu arttıkça artarken pişmiş köfte örneklerinde pişmeyle birlikte L*ve b* değerleri azalmıştır. Lupin unu ilave edilerek üretilen beyaz ekmek ve makarna üretimi yapılan çalışmalarda lupin un miktarı arttıkça L değerinin azaldığını belirtmişlerdir (Tuluk, 2017; Yaver ve Bilgili, 2021). Lupin ilave edilen çiğ köfte örneklerinin a* kırmızı değeri artarken pişmiş köfte örneklerinde pişmeyle a* değeri artış göstermiştir.

Tablo 3. Deneysel örneklere ait renk analiz bulguları

Örnekler		***L****	***a****	***b****
Çiğ Ürün	**% 10**	33,82 ± 0,18	18,33 ± 0,09	26,73 ± 0,06
	% 20	38,36 ± 0,30	19,34 ± 0,65	29,84 ±0,27
	% 30	45 ± 0,23	21,82 ± 0,61	36,95 ± 0,03
Pişmiş Ürün	**% 10**	16,54 ± 0,27	22,46 ± 0,74	27,46 ± 0,06
	% 20	15,19 ± 0,14	24,23 ± 0,20	26,07 ± 0,19
	% 30	12,14 ± 0,27	27,19 ± 0,77	21,27 ± 0,61

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KENEVIR TOZUNUN YOĞURT KALITE PARAMETRELERI ÜZERINE ETKISI

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ÖZET

Bu çalışma, kenevir tozu (Cannabis sativa L.) ilavesinin, yoğurt formülasyonlarının fizikokimyasal, mikrobiyolojik ve duyusal kalite parametreleri üzerindeki etkilerini incelemeyi amaçlamıştır. Kenevir tozu, yoğurt üretimine %1, %2 ve %3 olmak üzere üç farklı konsantrasyonda eklenmiş ve bir kontrol grubu ile detaylı olarak karşılaştırılmıştır. Elde edilen yoğurt örneklerinde; pH, titrasyon asitliği, renk değerleri (L^*, a^*, b^*) ve laktik asit bakteri sayıları gibi kritik parametreler değerlendirilmiştir. Ek olarak, tüketici kabul düzeylerini belirlemek amacıyla duyusal analizler gerçekleştirilmiştir. Araştırma bulguları, kenevir tozunun yoğurdun fonksiyonel özelliklerini önemli ölçüde zenginleştirdiğini göstermekle birlikte, yüksek ilave oranlarının ürünün duyusal kabulünü olumsuz yönde sınırlayabileceğini ortaya koymuştur.

Anahtar Kelimeler: Yoğurt, kenevir tozu, kalite parametreleri, fonksiyonel gıda, duyusal analiz

THE EFFECT OF HEMP POWDER ON YOGURT QUALITY PARAMETERS

ABSTRACT

This study aimed to investigate the effects of adding hemp powder (Cannabis sativa L.) at different concentrations to a yogurt formulation on its physicochemical, microbiological, and sensory quality parameters. Hemp powder was incorporated into yogurt production at concentrations of 1%, 2%, and 3%, and compared with a control group. Key parameters such as pH, titratable acidity, color values (L^*, a^*, b^*), and lactic acid bacteria count were evaluated. Additionally, consumer acceptability levels were determined through sensory analysis. The results indicated that hemp powder significantly enhanced the functional properties of the yogurt; however, high inclusion rates were found to restrict sensory acceptance.

Keywords: Yogurt, hemp powder, quality parameters, functional food, sensory analysis

Giriş

Kenevir (Cannabis sativa L.), Cannabaceae familyasından yıllık otsu bir bitkidir. Kenevir, tarih boyunca insanlar tarafından lif ve yağ içeriğinden dolayı tekstil ve gıda amaçlı kullanımı yaygın olarak belgelenmiştir (Rizzo ve ark., 2023). Kenevir tohumları, yüksek esansiyel amino asit içeriğiyle yansıtılan yüksek biyolojik değere sahip oldukça yüksek protein içeriği (%22,17) ile öne çıkmaktadır. Bununla beraber, kenevir tohumları, faydalı yağ asidi yapısının eklendiği yağ içeriği (%26,25- 37,50) nedeniyle yüksek bir enerji değerine sahiptir (Capcanari ve ark., 2023). Kenevir tohumundan elde edilen un veya tozu içerdiği besin maddeleri nedeniyle fonksiyonel gıda bileşeni olarak dikkat çekmektedir (Callaway, 2004; House ve ark., 2010).Kenevir tozunun protein içeriği oldukça yüksektir (%30–50) ve başlıca fraksiyonları edestin ve albuminden oluşmaktadır. Edestin, insan plazma globulinlerine benzer yapıda olduğundan biyoyararlanımı yüksektir ve esansiyel aminoasit profili açısından dengeli bir kaynak olarak kabul edilmektedir (House et al., 2010; Tanase Apetroaei ve ark., 2024). Özellikle arginin, lösin ve glutamik asit miktarı dikkate değer düzeydedir. Bu özellikleri sayesinde kenevir proteini, sporcu beslenmesinde ve bitkisel protein takviyesi gereken diyetlerde önemli bir alternatif haline gelmiştir (Palmer et al., 2020). Kenevir tozunun önemli bir diğer bileşeni ise çözünür ve çözünmez diyet lifleridir. Bu lifler sindirim sağlığını destekler, prebiyotik etki gösterir ve bağırsak mikrobiyotasının düzenlenmesine katkı sağlar (Cunnane et al., 1999; Odeeka ve ark., 2022). Mineral açısından da zengin olan kenevir tozu; magnezyum, fosfor, potasyum, demir, çinko ve kalsiyum gibi elementlerin yanı sıra E vitamini ve B grubu vitaminlerini de içermektedir (Leizer et al., 2000). Kenevir tohumlarının yağa işlenmesi sırasında tohumdaki yağın büyük kısmı çıkarılmış olsa da, kalıntı yağ fraksiyonları zengin **omega-3 ve omega-6 yağ asitleri** içerir. Bu yağ asitleri yaklaşık 3:1 oranında bulunmakta olup, insan sağlığı için önerilen ideal dengeyi sağlamaktadır Ayrıca gamma-linolenik asit (GLA) gibi özel yağ asitleri de antiinflamatuvar özellik göstermektedir. (Callaway, 2004; Rizzo ve ark., 2023;Yıldız, 2025). Gıda endüstrisinde yapılan çalışmalarda, kenevir tozunun ekmek, bisküvi, süt ürünleri ve bitkisel içeceklere ilavesinin ürünlerin besin değerini artırdığı; ancak yüksek düzeyde kullanımının duyusal özelliklerde bazı olumsuzluklara yol açabileceği vurgulanmaktadır (Yadav et al., 2021). Sağlık üzerindeki etkilerine bakıldığında, kenevir proteini ve liflerinin **kolesterol düşürücü, antioksidan, antiinflamatuvar ve antihipertansif** özelliklere sahip olduğu bildirilmektedir (Rodriguez-Leyva & Pierce, 2010). Özellikle arginin içeriği, nitrik oksit üretimini artırarak damar sağlığını olumlu etkilemektedir. Bu nedenle kenevir tozu, fonksiyonel gıda üretiminde potansiyel bir katkı maddesi olarak görülmektedir.

Yoğurt, fermente süt ürünleri arasında en yaygın tüketilen gıdalardan biridir ve besinsel değeri ile fonksiyonel özellikleri nedeniyle sağlıklı beslenmenin önemli bir bileşenidir. Son yıllarda tüketici talebi, yalnızca temel besin öğelerini sağlayan ürünlerden ziyade, sağlık üzerinde ilave faydalar sunan **fonksiyonel gıdalar**a yönelmiştir (Granato et al., 2010). Bu bağlamda yoğurt formülasyonlarında çeşitli bitkisel toz ve ekstraktların kullanımı giderek artmaktadır. Bu çalışmada kenevir tozunun farklı oranlarda yoğurt üretimine ilavesinin kalite parametreleri ve duyusal kabul üzerindeki etkilerini incelemek amaçlanmıştır.

Materyal

Çalışmada pastörize inek sütü, ticari yoğurt starter kültürü (Streptococcus thermophilus ve Lactobacillus delbrueckii subsp. bulgaricus) ve düşük THC içerikli endüstriyel kenevir tohumu tozu kullanılmıştır.

Deneysel yoğurt örnekleri kontrol (Kenevir tozu eklenmemiş yoğurt), %1 (A), %2 (B) ve %3 (C) kenevir tozu eklenmiş yoğurtlar şeklinde dört grupta hazırlanmıştır.

Süt 85 °C'de 30 dakika ısıl işlem görmüş, 42 °C'ye soğutulmuş ve starter kültür ile inoküle edilmiştir. Kenevir tozu inokülasyon öncesinde sütte çözünür hale getirilerek homojenize edilmiştir. Fermantasyon 42 °C'de pH 4,6'ya ulaşıncaya kadar sürdürülmüş, ardından 4 °C'de 24 saat olgunlaştırılmıştır.

Metot

Deneysel örneklerin pH değeri pH metre ile ölçülmüştür (AOAC). Titrasyon asitliği % laktik asit cinsinden titrasyon metodu ile yapılmıştır. Renk analizi Minolta cihazı ile CIELab sisteminde L*, a*, b* değerleri belirlenmiştir. Laktik asit bakteri sayımı M17 agar kullanılarak 37 C' de 24 h sonunda sayılmıştır. 8 kişilik panelist grup 1 çok kötü, 2 kötü, 3 iyi, 4 normal ve 5 çok iyi şeklinde deneysel örnekleri renk, koku, lezzet, kıvam, homojen görünüm ve genel beğeni açısından değerlendirmiştir.

Bulgular

Mikrobiyolojik ve Kimyasal Analiz Sonuçları

Deneysel örneklere ait kimyasal ve mikrobiyolojik analiz bulguları Tablo 1 de verilmiştir. Kenevir tozu ilavesinin yoğurdun fizikokimyasal ve mikrobiyolojik özellikleri üzerinde belirgin etkiler yarattığı tespit edilmiştir. Kenevir tozu oranı arttıkça, yoğurt örneklerinin pH değeri kontrol grubu (4.42) ile karşılaştırıldığında, en yüksek konsantrasyonda (C grubu) 3.98'e kadar düşerek önemli bir azalma göstermiştir. Bu pH düşüşüne rağmen, titrasyon asitliği (laktik asit yüzdesi) kontrol grubundaki %8.53'ten C grubunda %7.43'e gerileyerek, kenevir tozunun yoğurt matrisinde tamponlama kapasitesi oluşturduğunu veya asit oluşumunu dolaylı olarak etkilediğini düşündürmektedir. Mikrobiyolojik açıdan bakıldığında ise, kenevir tozu yoğurt kültürlerinin aktivitesini desteklemiştir. Kontrol grubunda 6.19 log10 kob/g olan laktik asit bakteri sayısı, %3 kenevir tozu içeren C grubunda 7.55 log10 kob/g'a yükselmiştir. Bu artış, kenevir tozunun laktik asit bakterileri için büyüme faktörü görevi görerek yoğurdun probiyotik potansiyelini artırdığını göstermektedir. Genel olarak, kenevir tozu, yoğurtta mikrobiyolojik aktiviteyi teşvik ederken, pH ve laktik asit dengesini karmaşık bir şekilde etkilemektedir.

Tablo 1. Deneysel örneklerin kimyasal ve mikrobiyolojik analiz bulguları

Analiz	K	A	B	C
pH	4.42	4.40	4.01	3.98
% laktik asit	8.53	8.42	7.98	7.43
Laktik asit bakteri sayısı (log 10 kob/g)	6.19	6.11	7.42	7.55

Renk Analiz Sonuçları

Yoğurt örneklerinin renk analiz bulguları, kenevir tozu ilavesinin ürünün yüzey rengi üzerinde önemli bir etkiye sahip olduğunu göstermektedir. En belirgin değişim, yoğurt örneklerinin parlaklık (*L**) değerlerinde gözlenmiştir; kontrol grubu 88.23 değeri ile en açık renge sahipken, kenevir tozu konsantrasyonu arttıkça *L** değeri önemli ölçüde azalmıştır. En yüksek koyulaşma, 75.56 *L** değeriyle %2 kenevir tozu içeren B grubunda kaydedilmiştir. Bu düşüş, kenevir tozunun doğal koyu rengi ile ilişkilidir. Aynı zamanda, sarımsılık (*b**) değeri de kenevir tozu ilavesiyle sürekli olarak artmıştır; K grubunda *b** değeri 8.92 iken, en yüksek konsantrasyon olan C grubunda bu değer 12.41'e yükselmiştir. Bu artış, kenevir tozunun yapısındaki doğal sarı/kahverengi pigmentlerin yoğurt matrisine geçişiyle açıklanabilir.

Kırmızımsılık/yeşilimsilik göstergesi olan *a** değeri ise, tüm örneklerde negatif (yeşilimsi) bölgede kalmış ve %3 kenevir tozu içeren C grubu 3.20 değeri ile en yüksek yeşilimsi tonu göstermiştir. Sonuç olarak, kenevir tozu yoğurdun görünümünü daha koyu, daha sarı ve hafif yeşilimsi bir tona doğru değiştirmiştir.

Tablo 2. Deneysel örneklerin renk analiz bulguları

Analiz	K	A	B	C
*L**	88.23	83.56	75.56	78.12
*a**	-2.16	-2.11	-2.10	-3.2
*b**	8.92	9.63	11.99	12.41

Duyusal Analiz Sonuçları

Deneysel yoğurt örneklerinin duyusal analiz bulguları (Tablo 3), kenevir tozu ilavesinin tüketici kabulü üzerindeki eşiğini net bir şekilde ortaya koymuştur. Kontrol grubu (K) ve %1 kenevir tozu içeren A grubu, tüm parametrelerde en yüksek puan olan 5'i alarak genel beğeni açısından birbirinden farksız kabul edilmiştir. Buna karşın, kenevir tozu konsantrasyonunun %2 (B) ve %3 (C) oranlarına yükselmesiyle birlikte duyusal kabulde belirgin bir düşüş gözlenmiştir. Özellikle C grubunda renk puanı 3.1'e, genel beğeni puanı ise 3.9'a gerilemiştir. Koku ve lezzet gibi kritik kabul parametreleri de B ve C gruplarında düşüş. Buna karşılık, kıvam ve homojen görünüm gibi tekstürel özellikler, en yüksek ilave oranında bile 5 puanını koruyarak kenevir tozunun yoğurdun yapısal bütünlüğünü olumsuz etkilemediğini göstermiştir. Duyusal değerlendirmeler, %2 ila %6 oranında kenevir unu veya küspe unu içeren yoğurtların iyi bir kabul düzeyini koruduğunu, tat ve doku açısından ise genellikle %4 konsantrasyonun en iyi olarak derecelendirildiğini göstermektedir. Daha yüksek konsantrasyonlar topraksı veya büzücü (astringent) tatlar getirebilir, ancak bunlar tatlandırıcılar veya vanilya ve agav şurubu gibi aroma vericiler ile hafifletilebilir (Nakov ve ark., 2023; Hashemian ve Nouri, 2023) Kenevir ilavesi fermantasyon sürecini engellememektedir; laktik asit bakterileri canlı kalmakta ve ürünün raf ömrü standart yoğurtlarla karşılaştırılabilir düzeyde olmaktadır Łopusiewicz ve ark., 2022; Nakov ve ark., 2023)

Tablo 3. Deneysel örneklerin duyusal analiz bulguları

Parametre	K	A	B	C
Koku	5	5	4.2	4.1
Renk	5	4.9	3.6	3.1
Lezzet	5	5	3.8	4
Kıvam	5	5	5	5
Homojen görünüm	5	5	5	5
Genel beğeni	5	5	4	3.9

Tartışma

Bu çalışmanın bulguları, kenevir tozunun yoğurt formülasyonlarına dahil edilmesinin ürüne önemli fonksiyonel katkılar sağladığını ancak yüksek konsantrasyonlarda duyusal sınırlamalar getirdiğini göstermiştir. Kenevir tozu ilavesi, yoğurt kültürlerinin aktivitesini destekleyerek laktik asit bakteri sayısını anlamlı ölçüde yükseltmiştir, bu da ürünün probiyotik potansiyelini artırmıştır. Fizikokimyasal analizlerde, artan kenevir tozu miktarına paralel olarak pH değeri düşmüş, ancak bu durum titrasyon asitliğinde düşüşle sonuçlanmış, kenevir tozunun yoğurt matrisinde tamponlama etkisi yarattığını düşündürmüştür. Renk analizleri, tozun doğal pigmentleri nedeniyle parlaklık değerini düşürerek ürünü koyulaştırdığını ve sarılık değerini önemli ölçüde artırdığını ortaya koymuştur. Duyusal değerlendirmede, tüketici kabulünün %1 ilave oranına kadar korunduğu, ancak %3'lük en yüksek konsantrasyonda renk ve genel beğeni puanlarının belirgin şekilde düştüğü tespit edilmiştir. Sonuç olarak, kenevir tozu yoğurt kalitesini biyolojik açıdan zenginleştirmek için değerli bir bileşen olmasına rağmen, bu faydaları korumak ve aynı zamanda tüketicinin duyusal beklentilerini karşılamak için optimum ilave konsantrasyonunun %1 civarında tutulması gerektiği sonucuna varılmıştır.

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A VALUABLE MARINE-BASED OMEGA-3 SOURCE: ANTARCTIC KRILL OIL

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ABSTRACT

Antarctic krill oil, obtained from *Euphausia superba*, due to its distinct composition, nutritional and functional potentials has emerged as a valuable food source for humans. Omega-3 fatty acids are classified into three types: alpha-linolenic acid (ALA 18:3), eicosapentaenoic acid (EPA 20:5), and docosahexaenoic acid (DHA 22:6). ALA is derived from plant sources, whereas EPA and DHA are commonly known as marine-based omega-3s. Marine organisms such as microalgae, krill, and fish are abundant natural sources of phospholipids enriched with EPA and DHA. Antarctic krill oil is a red viscous liquid obtained from Antarctic krill, a small crustaceans that can be found in all the world's oceans, but mostly in the Northern and Southern polar seas. Many people ask why krill oil is so much stronger than fish oil. Antarctic krill oil, which has been considered an alternative to fish oil since krill is rich in nutrients, including vitamins A and E, minerals, phospholipids, astaxanthin and flavonoids, high level omega-3 polyunsaturated fatty acids has been drawing increasing attention. This review aims to provide an overview of the chemical composition, health advantages and current applications of Antarctic krill oil.

Keywords: Antarctic krill oil, Omega-3, Minor components, Fatty acids

Introduction

Fats are the most concentrated energy source in the human diet and are classified as saturated (SFA), monounsaturated (MUFA), or polyunsaturated fatty acids (PUFA) according to the number of double bonds. Lipids play crucial roles in human physiology, including energy production, maintaining membrane integrity, and facilitating signal transduction. Omega-3 long-chain PUFAs eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which help preserve cellular membrane structure, regulate inflammatory responses and support cardiovascular and neurological function. Because humans cannot synthesize EPA and DHA on their own, these fatty acids must be obtained through the diet, primarily from marine sources such as fish, krill, shellfish, and microalgae. Antarctic krill oil has recently emerged as a notable dietary supplement rich in omega-3 PUFAs, with EPA and DHA. Besides these essential fatty acids, marine oils are a source of important bioactive compounds like astaxanthin while marine organisms such as microalgae, krill, and fish (Zhu et al., 2015; Zhao et al., 2020; Attri et al., 2025; He et al., 2025; Machaj et al., 2025; Su et al., 2025; Wei et al., 2025;). Antarctic krill (*Euphausia superba*) is a common crustacean plankton species in Antarctic oceans, with biomass reserves estimated at 600 million to 1 billion tons and an annual harvest of 60-100 million tons. Antarctic krill is a marine resource containing a high concentration of n-3 polyunsaturated fatty acids. Antarctic krill oil, a red viscous functional oil derived from this species, is gaining popularity due to its favorable fatty acid composition and high antioxidant capabilities. Krill oil includes a high concentration of phospholipids and phospholipid-bound omega-3 PUFAs, as well as bioactive components such astaxanthin, tocopherols, flavonoids, vitamins, and minerals, making it an important source of nutritional elements (Sati and Bhatt 2018; Cui et al., 2025; Dong et al., 2025; Wei et al., 2025; Zhang et al., 2025). Krill has an important ecological role as a key food supply for many fish species and bigger marine animals. Krill oil, have also earned commercial and scientific attention; in 2008, the U.S. Food and Drug Administration (FDA) designated krill oil as generally recognized as safe (GRAS) (Xie et al., 2019; Colletti et al., 2021; Shahidi and Abad 2024; Sarıyer et al., 2025). Antarctic krill was originally used primarily as an ingredient in aquaculture feeds. Antarctic krill oil has recently gained popularity due to its diverse bioactive components and associated health benefits, indicating potential applications in pharmacological and nutraceutical products aimed at cardiometabolic, neurodegenerative, and other disease conditions. However, it's usage in the food sector is limited due to issues such as poor oxidative stability, a strong off-flavor, and low astaxanthin bioavailability (Colletti et al., 2021; Lin et al., 2024; Cui et al., 2025). This review aims to provide an overview of the chemical composition, health advantages and current applications of Antarctic krill oil.

Chemical Composition, Health Benefits and Current Applications of Antarctic Krill Oil

Krill oil exhibits a remarkably complex chemical profile distinguished from conventional edible oils, which generally contain more than 95% triacylglycerols. In contrast, krill oil is dominated by phospholipids, followed by triacylglycerols, diacylglycerols, monoacylglycerols, free fatty acids, and other minor lipid classes. It provides a wide spectrum of fatty acids, including substantial levels of C14:0, C16:0, C16:1, C18:1, C20:1, and high amounts of the long-chain n-3 PUFAs EPA (C20:5) and DHA (C22:6), which are well recognized for their essential roles in human health. In addition to these lipids, krill oil contains phospholipid-derived fatty acids, choline, and a significant fraction of sterols (2.3–3.9% of total lipids), predominantly desmosterol and cholesterol. Its vivid deep-red coloration is attributable to astaxanthin, the primary carotenoid present in various marine organisms and algae, which contributes potent antioxidant activity. Krill oil is also enriched with α-tocopherol, the major tocopherol species that accounts for more than 90% of its vitamin E content and provides synergistic antioxidant

effects alongside astaxanthin. Beyond the oil fraction, whole Antarctic krill contains high-quality proteins rich in essential amino acids such as taurine, glycine, arginine, and alanine, as well as considerable levels of minerals including magnesium, calcium, and phosphorus, making it a promising raw material for nutritional product development. Antarctic krill oil is a valuable nutritional source notable for its unique composition and functional properties. It contains a high proportion of phospholipids predominantly phosphatidylcholine, which enhances the bioavailability of its omega-3 fatty acids. The oil is particularly rich in EPA (20:5 n−3) and DHA (22:6 n−3), long-chain omega-3 PUFAs essential for human health. In addition, krill oil contains minor but important bioactive compounds, including sterols, astaxanthin, vitamins, and minerals. This combination of high phospholipid content, bioavailable omega-3s, and potent antioxidant components underscores the potential of Antarctic krill oil as a functional food and nutraceutical ingredient (Kwantes and Grundmann 2015; Xie et al., 2019; Colletti et al., 2021; Shahidi and Abad 2024; Attri et al., 2025; Luo et al., 2025; Wei et al., 2025)

Euphausia superba has recently emerged as a significant nutraceutical resource, thanks to its high levels of EPA, DHA, and astaxanthin. Krill oil is now broadly accessible in supplement form, including capsules, soft gels, tablets, and chewables. Its recognized benefits for cardiovascular and cognitive health, as well as its strong anti-inflammatory effects, have boosted its role in the global health and nutrition industry (Colletti et al., 2021; Shahidi and Abad 2024; Attri et al., 2025). Krill oil is an abundant source of long-chain omega-3 polyunsaturated fatty acids (LC-PUFAs), especially eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). In addition, it contains phospholipids, tocopherols, vitamin A, and the potent antioxidant astaxanthin. Together, these compounds offer a variety of well-documented health benefits. EPA and DHA from krill oil have demonstrated notable pharmacological effects in managing chronic conditions such as cardiovascular, neurological, inflammatory, metabolic, and neoplastic diseases, while also supporting a healthy gut microbiota. According to several studies, the astaxanthin in krill oil present at higher levels than in many fish oils boosts antioxidant capacity and may help protect eye health and retinal cells. Krill oil has also been shown to provide neuroprotective benefits, supporting cognitive function and potentially helping to prevent neurodegenerative diseases like Alzheimer's. Further studies highlight its anti-obesity, anti-diabetic, anti-cancer, and women's health benefits, such as easing emotional and physical symptoms of premenstrual syndrome (PMS). Thanks to its diverse bioactive components, krill oil stands out as a valuable marine supplement with broad therapeutic potential (Sati and Bhatt 2018; Xie et al., 2019; Zhao et al., 2020; Colletti et al., 2021; Shahidi and Abad 2024; Attri et al., 2025; Sarıyer et al., 2025).

Conclusion

Antarctic krill oil (AKO) is regarded as a superior marine lipid source due to its distinct composition, which includes omega-3 long-chain polyunsaturated fatty acids that are mainly esterified to phospholipids, considerably increasing their bioavailability. AKO also contains a variety of bioactive components such as astaxanthin esters, vitamin A, tocopherols, and phospholipid-type n-3 PUFAs, which contribute to its antioxidant, anti-inflammatory, and health-promoting effects. Krill oil is extremely susceptible to oxidation, better encapsulating solutions are required to improve its oxidative stability and shelf life. In future studies, innovative technologies for krill oil can be developed and novel encapsulation systems can be designed to increase the positive effects of human health.

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FONKSİYONEL GIDA SİSTEMLERİNDE MİKROENKAPSÜLASYONUN FENOLİK VE ANTİOKSİDAN BİLEŞİKLERİN STABİLİTESİ ÜZERİNE ETKİLERİ

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ÖZET

Mikroenkapsülasyon, gıda endüstrisinde ısıya, ışığa, oksijene ve pH değişimlerine duyarlı biyoaktif bileşenlerin korunmasında kullanılan etkili bir teknolojidir. Fenolik ve antioksidan bileşikler doğal olarak yüksek biyolojik aktiviteye sahip olmalarına rağmen çevresel koşullara karşı oldukça hassastır. Bu nedenle mikroenkapsülasyon, bu bileşiklerin oksidatif ve termal bozulmalarını azaltarak fiziksel, kimyasal ve biyolojik stabilitelerini artırır. Mikroenkapsülasyon işlemi sırasında fenolik bileşikler, maltodekstrin, gum arabik, nişasta türevleri, kazein veya polisakkaritler gibi duvar materyalleriyle kaplanarak çevresel etkilere karşı koruyucu bir bariyer içine alınır. Bu yapı, oksijenin difüzyonunu sınırlar, ışık ve ısıya maruziyeti azaltır, böylece bileşiklerin raf ömrü ve toplam antioksidan kapasitesi korunur. Aynı zamanda mikroenkapsülasyon, fenolik bileşiklerin biyoyararlanımını artırır ve sindirim sisteminde kontrollü salım sağlayarak etkinliğini sürdürür. Antioksidan aktivite bakımından mikroenkapsülasyon, bileşiklerin oksijen ve serbest radikallerle doğrudan temasını önleyerek degradasyonu yavaşlatır. Özellikle dondurarak kurutma (liyofilizasyon) ve emülsiyon bazlı sistemler, düşük sıcaklıkta işlem gördükleri için fenoliklerin %90'ına kadarının korunmasını sağlar. Sprey kurutma gibi yüksek sıcaklıklı yöntemlerde ise belirli kayıplar oluşabilmektedir. Mikroenkapsülasyon fenolik bileşiklerin gıda matrislerinde oluşturabileceği olumsuz tat, renk veya etkileşimleri minimize ederken, fonksiyonel ürünlerde duyusal kaliteyi ve homojen dağılımı geliştirir. Bu nedenle, uygun yöntem ve duvar materyali seçimi ile fenolik ve antioksidan bileşiklerin korunması, gıdaların fonksiyonel, besleyici ve duyusal kalitesinin artırılmasında kritik rol oynar. Mikroenkapsülasyon; fenolik ve antioksidan bileşiklerin stabilitesini, biyoyararlanımını ve fonksiyonel etkinliğini artıran, gıda teknolojisinde hem koruma hem de kontrollü salım amacıyla yaygın biçimde kullanılan yenilikçi bir yöntemdir.

Anahtar Kelimeler: Mikroenkapsülasyon, fenolik bileşikler, antioksidan kapasite, stabilite.

EFFECTS OF MICROENCAPSULATION ON THE STABILITY OF PHENOLIC AND ANTIOXIDANT COMPOUNDS IN FUNCTIONAL FOOD SYSTEMS

ABSTRACT

Microencapsulation is an effective technology used in the food industry to protect bioactive compounds that are sensitive to heat, light, oxygen, and pH changes. Although phenolic and antioxidant compounds naturally possess high biological activity, they are highly sensitive to environmental conditions. Therefore, microencapsulation increases the physical, chemical, and biological stability of these compounds by reducing their oxidative and thermal degradation. During the microencapsulation process, phenolic compounds are coated with wall materials such as maltodextrin, gum arabic, starch derivatives, casein, or polysaccharides, enclosing them in a protective barrier against environmental effects. This structure limits oxygen diffusion and reduces exposure to light and heat, thereby preserving the shelf life and total antioxidant capacity of the compounds. At the same time, microencapsulation increases the bioavailability of phenolic compounds and maintains their effectiveness by providing controlled release in the digestive system. In terms of antioxidant activity, microencapsulation slows degradation by preventing direct contact between the compounds and oxygen and free radicals. Freeze-drying (lyophilization) and emulsion-based systems, in particular, preserve up to 90% of phenolics because they are processed at low temperatures. Certain losses may occur with high-temperature methods such as spray drying. Microencapsulation minimizes the negative taste, color, or interactions that phenolic compounds can cause in food matrices, while improving sensory quality and homogeneous distribution in functional products. Therefore, the protection of phenolic and antioxidant compounds through the selection of appropriate methods and wall materials plays a critical role in enhancing the functional, nutritional, and sensory quality of foods. Microencapsulation is an innovative method widely used in food technology for both protection and controlled release purposes, which increases the stability, bioavailability, and functional efficacy of phenolic and antioxidant compounds.

Keywords: Microencapsulation, phenolic compounds, antioxidant capacity, stability.

Giriş

Fenolik bileşikler ve doğal antioksidanlar, bitkisel gıdalarda yaygın olarak bulunan ve hem gıda kalitesinin korunmasında hem de insan sağlığının desteklenmesinde önemli roller üstlenen biyolojik olarak aktif maddelerdir. Bu bileşikler; oksidatif stresin azaltılması, inflamatuar süreçlerin baskılanması, kardiyovasküler hastalık riskinin düşürülmesi, metabolik fonksiyonların düzenlenmesi ve bağırsak mikrobiyotasının modülasyonu gibi pek çok yararlı etkiye sahiptir (Scalbert vd., 2005; Shahidi ve Ambigaipalan, 2015). Fenolik bileşikler; flavonoidler, fenolik asitler, stilbenler ve lignanlar gibi geniş bir sınıflandırmaya sahiptir ve çay, kahve, kakao, meyveler, sebzeler, zeytinyağı, baklagiller ve tahıllar gibi çok sayıda gıdada doğal olarak bulunur. Ancak tüm bu olumlu etkilerine rağmen polifenoller ve antioksidan bileşikler, çevresel koşullar ve gıda işleme süreçlerine karşı oldukça duyarlıdır. Isı, ışık, oksijen, enzimatik aktivite ve pH değişimleri gibi faktörler bu bileşiklerin yapısını bozarak biyolojik etkinliklerinin azalmasına yol açmaktadır (Halliwell, 2012). Fenolik bileşiklerin hızlı oksidasyonu ve düşük biyoyararlanımı, bu bileşenlerin doğrudan gıdaya eklenmesiyle istenen fonksiyonel etkinin elde edilmesini güçleştirmektedir (Shahidi ve Yeo, 2018). Bu nedenle, polifenoller ve antioksidanların korunmasına yönelik yeni teknolojilere ihtiyaç duyulmuştur. Mikroenkapsülasyon, hassas biyoaktif bileşenleri korumak, stabilitesini artırmak ve kontrollü salım sağlamak için gıda teknolojisinde öne çıkan yenilikçi bir yöntem olarak önem kazanmıştır. Mikroenkapsülasyonun fonksiyonel gıdalar alanında kullanımı son yıllarda önemli ölçüde artmış ve fenolik–antioksidan bileşiklerin etkinliğini sürdürmede stratejik bir araç hâline gelmiştir (Mehta vd., 2022; Ordóñez-García vd., 2024; Bińkowska vd., 2024).

1. Fenolik Ve Antioksidan Bileşikler

Fenolik ve antioksidan bileşikler, bitkisel kaynaklı gıdalarda doğal olarak bulunan ve hem gıda kalitesinin korunmasında hem de insan sağlığının desteklenmesinde kritik rol oynayan biyoaktif maddelerdir. Kimyasal olarak, bir veya birden fazla aromatik halkaya bağlı hidroksil gruplarından oluşan bu bileşikler; flavonoidler, fenolik asitler, stilbenler ve lignanlar gibi geniş bir alt sınıflandırmaya sahiptir (Shahidi ve Ambigaipalan, 2015). Bitkilerde ikincil metabolit olarak üretilen fenolik bileşikler, çevresel stres faktörlerine (UV ışık, patojen saldırıları, oksidatif stres) karşı koruyucu görev üstlenirken; insan diyetinde ise fonksiyonel ve terapötik etki gösteren önemli doğal antioksidanlardır.

1.1. Gıdalarda bulunuşu ve teknolojik önemi

Fenolik bileşikler; meyveler, sebzeler, çay, kahve, kakao, zeytinyağı, tahıllar, baklagiller ve baharat gibi birçok gıdada doğal olarak bulunur. Gıdalara karakteristik renk, aroma ve tat özelliklerini kazandırmaları nedeniyle duyusal kalite üzerinde belirleyici rol oynarlar. Flavonoidler, meyve ve sebzelerin parlak renklerinden sorumlu iken; fenolik asitler ve tanenler burukluk ve acılık gibi tat özelliklerini etkiler (Scalbert vd., 2005). Fenolikler, gıdalarda oksidatif bozulmayı geciktirerek raf ömrünü uzatan doğal antioksidanlar olarak da işlev görür. Bu özellik, özellikle yağ içeriği yüksek ürünlerde (zeytinyağı, kuruyemişler, et ürünleri) önemli bir teknolojik avantaj sağlar**.**

1.2. Antioksidan kapasiteleri ve sağlık etkileri

Fenolik bileşiklerin en önemli özelliği, güçlü antioksidan kapasiteleridir. Serbest radikalleri nötralize etme, metal iyonlarını şelatlama ve oksidatif zincir reaksiyonlarını durdurma yetenekleri sayesinde hücresel hasarın önlenmesine katkı sağlarlar (Halliwell, 2012). Bu etkinin biyolojik yansımaları oldukça geniştir**.**

1.2.1. Kardiyovasküler hastalıklara karşı koruma

Polifenoller, LDL oksidasyonunu azaltır, damar duvarı fonksiyonunu iyileştirir ve inflamatuar mediyatörlerin üretimini baskılar (Shahidi ve Yeo, 2018). Bu sayede ateroskleroz gelişimi yavaşlamakta ve kardiyovasküler hastalık riski azalmaktadır.

1.2.2. Anti-inflamatuar ve anti-kanser etkiler

Fenolik bileşikler NF-κB ve MAPK gibi inflamasyon yollarını modüle ederek anti-inflamatuar etki gösterir; hücre proliferasyonu ve apoptozu düzenleyerek anti-kanser potansiyel taşırlar (Scalbert vd., 2005).

1.2.3. Metabolik hastalıkları önleyici etkiler

Diyet polifenolleri; insülin hassasiyetini artırma, glukoz emilimini düzenleme ve lipid metabolizmasını iyileştirme gibi etkilerle diyabet ve obezitenin yönetiminde yardımcıdır (Kaushalya vd., 2024).

1.2.4. Nöroprotektif etkiler

Fenolik bileşikler, oksidatif stres kaynaklı nöronal hasarı azaltarak nörodejeneratif hastalıklara karşı koruyucu etki gösterebilir (Halliwell, 2012).

1.2.5. Bağırsak mikrobiyotası üzerine etkiler

Fenolik bileşikler bağırsak bakterileri tarafından metabolize edilerek sağlığa yararlı fenolik türevlerine dönüşür ve mikrobiyota kompozisyonunu olumlu yönde modüle eder (Shahidi ve Ambigaipalan, 2015). Bu etki, bağırsak bariyer fonksiyonunun korunması ve sistemik inflamasyonun azaltılması ile ilişkilendirilmektedir.

2. Fenolik Bileşiklerin Ve Antioksidanların Kararsızlığı

Fenolik bileşikler ve doğal antioksidanlar, kimyasal yapıları gereği birçok degradasyon mekanizmasına açıktır ve gıda işleme ile depolama koşullarında önemli kayıplar gösterebilir.

2.1. Isı duyarlılığı

Fenolik bileşiklerin çoğu yüksek sıcaklıklarda hızla okside olmakta veya degradasyona uğramaktadır. Pastörizasyon ve sterilizasyon gibi ısıl işlemler sırasında fenolik kayıplarının %20–70 arasında olabildiği bildirilmektedir (Rice-Evans vd., 1997). Bu durum, fonksiyonel gıdalarda hedeflenen antioksidan kapasitenin korunmasını güçleştirir.

2.2. Işığa duyarlılık

UV ve görünür ışık, fenolik bileşiklerin fotooksidasyonuna yol açarak renk, aroma ve antioksidan kapasite kaybına neden olur (Scalbert vd., 2005). Özellikle antosiyanin içeriği yüksek ürünlerde renk bozulması dikkat çekicidir.

2.3. Oksijen duyarlılığı

Fenolikler, özellikle kateşin ve gallik asit gibi yapılar, oksijen varlığında kolaylıkla oksitlenir ve bu süreçte hem antioksidan kapasite azalır hem de istenmeyen renk ve tat değişimleri ortaya çıkar (Halliwell, 2012). Zeytinyağı fenolleri, üzüm posası ekstraktları ve yağlı tohumlarda yapılan çalışmalar, oksijen maruziyetinin antioksidan kapasitede anlamlı azalmaya yol açtığını göstermektedir (Karrar vd., 2021).

2.4. pH değişimleri

pH, fenolik bileşiklerin iyonizasyon durumunu ve dolayısıyla stabilitesini doğrudan etkiler. Antosiyaninler düşük pH'ta daha stabil iken, nötral ve hafif alkali pH koşullarında hızla

bozunurlar (Shahidi ve Ambigaipalan, 2015). Gıda matrisine bağlı pH değişimleri fenolik bileşiklerin yapısal bütünlüğünü olumsuz yönde etkileyebilmektedir.

2.5. Düşük biyoyararlanım

Fenolik bileşiklerin çoğu, bağırsakta sınırlı çözünürlük ve hızlı metabolizma nedeniyle düşük biyoyararlanım gösterir (Shahidi ve Yeo, 2018). Bu nedenle canlı sistemlere ulaşan efektif doz düşüktür ve beklenen biyolojik etkinin tam olarak ortaya çıkması engellenebilir. Bu kararsızlık mekanizmaları, fenolik bileşiklerin doğrudan gıda ürünlerine eklenmesini sınırlamakta; fonksiyonel ürünlerde istenen sağlık etkilerinin sürdürülebilirliği için ek

koruyucu stratejiler gerektirmektedir. Mikroenkapsülasyon bu noktada temel bir teknolojik çözüm olarak öne çıkmaktadır (Mehta vd., 2022; Santos vd., 2020).

3. Mikroenkapsülasyon Ve Temel Prensipleri

Mikroenkapsülasyon, sıvı, katı veya gaz hâlindeki bir aktif bileşenin (çekirdek materyal), genellikle birkaç mikrometre ile birkaç yüz mikrometre çapında olacak şekilde koruyucu bir duvar veya kaplama materyali ile çevrilerek mikro ölçekte kapsüller hâline getirilmesi işlemidir. Bu teknolojide amaç, hassas veya işlevsel bir bileşiği çevresel koşullardan izole etmek, kontrollü salım sağlamak ve gıda sistemlerine daha stabil bir formda entegre etmektir.

Mikrokapsüller;

- çekirdeği dış ortamdan fiziksel olarak korur,
- kontrollü ve hedefli salıma imkân verir,
- bileşiğin çözünebilirliğini ve dağılımını iyileştirir,
- istenmeyen tat ve kokuları maskeleyebilir (Bińkowska vd., 2024; Mehta vd., 2022).

Bu nedenle mikroenkapsülasyon, hem teknolojik hem de biyolojik işlevleri iyileştiren çok yönlü bir taşıyıcı sistem teknolojisi olarak değerlendirilmektedir.

3.1. Mikroenkapsülasyon yöntemleri

Fonksiyonel gıda sistemlerinde en yaygın kullanılan yöntemler aşağıda özetlenmiştir.

3.1.1. Sprey kurutma (spray drying)

Emülsiyon veya süspansiyon hâlindeki karışımın sıcak hava akımıyla püskürtülerek hızla kurutulması esasına dayanır. Endüstriye en kolay ölçeklenen yöntemlerden biridir. Bitkisel ekstraktlar, yağlar ve fenolikçe zengin fraksiyonların toz mikrokapsüller hâlinde elde edilmesinde sıklıkla tercih edilmektedir (Pino vd., 2019; Santos vd., 2020; Pudžiuvelytė vd., 2025).

3.1.2. Dondurarak kurutma (freeze-drying / liyofilizasyon)

Isıya çok hassas bileşenler için uygun bir yöntemdir. Düşük sıcaklıklarda suyun süblimasyonla uzaklaştırılması sayesinde fenolik ve uçucu bileşiklerin daha iyi korunması mümkündür. Sprey kurutmaya göre enerji maliyeti daha yüksek olmakla birlikte, hassas biyoaktifler için üstün stabilite sağlayabilmektedir (Santos vd., 2020; Pudžiuvelytė vd., 2025).

3.1.3. Koaservasyon ve kompleks koaservasyon

Karşı yüklü biyopolimerlerin (örneğin jelatin–gum arabik, protein–polisakkarit kombinasyonları) faz ayrımıyla kapsül duvarı oluşturduğu yöntemdir. Hidrofobik çekirdeklerin (yağ, aroma, polifenol ekstraktı) kontrollü salımı için etkilidir ve kapsül morfolojisinin iyi kontrol edilmesine imkân verir (Bińkowska vd., 2024; Mehta vd., 2022).

3.1.4. Ekstrüzyon ve damlatma teknikleri

Aljinat, pektin veya karragenan gibi hidrojel oluşturucu duvar materyalleriyle damlatma yoluyla jel boncuklar hazırlanır. Özellikle probiyotik–polifenol kombinasyonlarında ve ısıya hassas bileşiklerde kullanılır; mide pH'sına dayanıklı, bağırsakta çözünebilen yapılar elde edilebilir (García vd., 2021).

3.1.5. Lipozomlar, nanoemülsiyonlar ve nanoenkapsülasyon

Fosfolipit veya yüzey aktif madde içeren sistemlerde, yağda çözünen fenoller ve karotenoidler gibi bileşiklerin taşınmasında kullanılır. Yüksek yüzey alanı sayesinde çözünürlük ve emilim artışı sağlar; kontrollü salım ve hedefli taşıma açısından önemlidir (Kaushalya vd., 2024; Li vd., 2023).

4. Mikroenkapsülasyonda Kullanılan Duvar Materyalleri

Duvar materyali seçimi, kapsülün fiziksel özelliklerini, enkapsülasyon verimini ve fenolik stabilitesini doğrudan etkiler. Genellikle karbonhidratlar, proteinler, lipidler veya bunların kombinasyonları kullanılmaktadır (Mehta vd., 2022;).

4.1. Karbonhidrat bazlı duvar materyalleri

Maltodekstrin:

Yüksek çözünürlük, düşük viskozite ve iyi film oluşturma kapasitesi nedeniyle en yaygın taşıyıcılardan biridir. Tek başına kullanıldığında emülsifiye edici özelliği sınırlıdır; bu nedenle genellikle protein veya gum arabik ile kombine edilir. Toz oluşumu ve akışkanlığı iyileştirir (Pino vd., 2019)

Gum arabik:

Protein fraksiyonu sayesinde doğal bir emülgatör olup yağ esaslı çekirdeklerin kapsüllenmesinde yüksek stabilite sağlar. Fenolikçe zengin ekstraktların enkapsülasyonunda maltodekstrine kıyasla daha yüksek antioksidan aktivite ve kapsül bütünlüğü sağlayabildiği bildirilmektedir (Santos vd., 2020).

Modifiye nişastalar, inülin ve diğer oligosakkaritler:

Çözünürlük, film oluşturma ve prebiyotik etki nedeniyle tercih edilmektedir. Karbonhidrat karışımlarının (örneğin maltodekstrin–gum arabik, maltodekstrin–inülin) fenolik retansiyonunu tek bileşenli sistemlere göre artırdığı çeşitli çalışmalarda gösterilmiştir (Moro vd., 2021).

4.2. Protein bazlı duvar materyalleri

Süt proteinleri (whey protein izolatı, whey protein konsantresi, sodyum kazeinat), jelatin ve bitkisel proteinler özellikle yağ fazı içeren sistemlerde güçlü emülgatör ve duvar materyali olarak görev yapar. Whey protein–maltodekstrin veya whey protein–polisakkarit kompleks koaservat sistemlerinin enkapsülasyon verimini, oksidatif stabiliteyi ve kontrollü salım özelliklerini iyileştirdiği bildirilmektedir (Zen vd., 2020).

4.3. Lipid bazlı ve hibrit sistemler

Katı lipid nanopartiküller, lipozomlar ve yağ-bazlı duvar materyalleri, yağda çözünür antioksidanların ve fenolikçe zengin yağların (örneğin zeytinyağı, fındık yağı) stabilizasyonunda kullanılmaktadır. Bu sistemler, özellikle çoklu doymamış yağ asitlerinin ve yağda çözünen fenollerin oksidatif bozulmasını geciktirmede etkilidir (Karrar vd., 2021;

Bińkowska vd., 2024). Karbonhidrat–protein–lipid hibrit sistemleri, hem oksidatif stabiliteyi hem de kontrollü salımı optimize etmek için geliştirilmektedir (Mehta vd., 2022).

Tablo 1. Mikroenkapsülasyonda Kullanılan Başlıca Duvar Materyaller

Duvar materyali	**Özellikleri**	**Örnek kaynaklar**
Maltodekstrin	Düşük viskozite, iyi çözünebilirlik, iyi film oluşturma	Pino vd., 2019; Santos vd., 2020
Gum arabik	Mükemmel film oluşturucu, iyi emülgatör, uçucu bileşenler için ideal	Santos vd., 2020
Whey protein konsantresi (WPC)	Yağ fazını iyi kapsüller, ısıl stabiliteyi artırır	Zen vd., 2020; Me vd., 2022
Kitosan	Pozitif yüklü; probiyotik ve fenolik kombinasyonlarında üstün koruma	García vd., 2021
İnülin	Prebiyotik etki, iyi film oluşturma, karbonhidrat karışımlarında faydalı	Moro vd., 2021; Mehta vd., 2022

5. Mikroenkapsülasyonun Fenolik Ve Antioksidan Stabilitesi Üzerine Etkileri

5.1. İşleme ve depolama sırasında stabilite

Çeşitli bitkisel ekstraktlarda yapılan çalışmalar, polifenol fraksiyonlarının mikroenkapsülasyon sonrası ısıl işleme ve depolama koşullarında daha yüksek stabilite gösterdiğini ortaya koymuştur. Aronia ve diğer meyve ekstraktlarının mikroenkapsülasyonu, toplam fenolik madde ve DPPH/FRAP antioksidan kapasitesinin serbest ekstraktlara kıyasla daha yavaş azaldığını göstermektedir (Pudžiuvelytė vd., 2025). Balkabağı yağı, siyah çay ekstraktı, üzüm posası ve farklı yağlı tohum sistemlerinde sprey kurutma ile elde edilen mikrokapsüller, oksidatif ranciditeyi azalttığı ve renk stabilitesini artırdığı yönünde rapor edilmiştir (Rajapaksha ve Shimizu, 2021; Bergesse vd., 2024). Zeytin yaprağı ve meyve kabukları gibi fenolikçe zengin ekstraktların uygun duvar materyalleriyle kapsüllenmesi, model gıda sistemlerinde antioksidan kapasitenin depolama süresince korunmasına katkı sağlamaktadır (Rosales vd., 2023). Genel olarak, enkapsülasyon verimlerinin %50–90 aralığında olduğu, kapsüllerin ısı, oksijen ve ışığa karşı serbest forma göre belirgin üstünlük sağladığı gösterilmektedir (Pudžiuvelytė vd., 2025).

5.2. Sindirim sonrası biyoerişilebilirlik ve biyoyararlanım

İn vitro sindirim modelleri, mikroenkapsüle polifenollerin gastrik fazda degradasyona karşı daha dirençli olduğunu, ince bağırsak fazında ise toplam fenolik içeriğin ve antioksidan aktivitenin serbest bileşiklere göre daha yüksek kaldığını göstermektedir (Kaushalya vd., 2024). Bazı nanoenkapsülasyon çalışmalarında, emilim fraksiyonunda anlamlı artışlar bildirilmiş; bu da mikroenkapsülasyonun yalnızca depolama stabilitesini değil, biyoerişilebilirliği de iyileştirerek fonksiyonel etkinliği güçlendirdiğini göstermektedir (Li vd., 2023).

5.3. Duyusal özelliklerin iyileştirilmesi

Mikroenkapsülasyon, polifenol kaynaklı acılık/burukluk, renk koyulaşması ve istenmeyen bitkisel tatların maskelemesinde de etkilidir. Özellikle fırıncılık ürünleri, süt ürünleri ve toz içecek karışımlarında, mikroenkapsüle yeşil çay, üzüm posası veya zeytin yaprağı

polifenollerinin ürün kabulünü düşürmeden antioksidan kapasiteyi artırdığı rapor edilmiştir (Ingale vd., 2025).

Tablo 2. Fenolik / Antioksidan Bileşiklerin Mikroenkapsülasyonu İle İlgili Seçilmiş Çalışmalar

Yazar (Yıl)	Biyoaktif bileşik	Yöntem	Duvar materyali	Ana bulgular
Rosales vd (2023)	Meyve kabuğu fenolleri	Nanoenkapsülasyon	Biyopolimer karışımları	İn vitro sindirim sonrası fenolik kaybı azaldı.
Zen vd (2020)	Spirulina antioksidanları	Mikroenkapsülasyon	Whey protein konsantresi	Fonksiyonel makarnada antioksidan aktivite stabil kaldı.
Li vd (2023)	Krill yağı antioksidanları	Nanoemülsiyon	Protein–polisakkarit sistemi	Oksidatif stabilite ve biyoerişilebilirlik arttı.
Pino vd (2019)	Balkabağı yağı	Sprey kurutma	Maltodekstrin	Oksidasyon hızı azaldı; raf ömrü uzadı.
García vd (2021)	Polifenol + probiyotik kombinasyonu	Jel boncuk (ekstrüzyon)	Kitosan / alginate	Probiyotik viabilitesi ve fenolik koruma arttı.

6. Fonksiyonel Gıda Sistemleri Açısından Kazanımlar

Mikroenkapsüle fenolik ve antioksidan bileşiklerin gıda formülasyonlarına entegrasyonu; fenolikçe zengin toz içecek karışımları, probiyotik ve polifenol kombinasyonlarını içeren fermente süt ürünleri, polifenoller ile zenginleştirilmiş unlu mamuller ve atıştırmalıklar, yağ fazı içinde fenollerle güçlendirilmiş fonksiyonel yağ ve emülsiyon sistemleri ile meyve–sebze yan ürünlerinin değerlendirildiği fonksiyonel toz ve ekstraktlar gibi pek çok ürün tipinin geliştirilmesine olanak sağlamaktadır. Ayrıca, meyve-sebze işleme yan ürünlerinden elde edilen polifenollerin mikroenkapsülasyon yoluyla fonksiyonel gıdalara kazandırılması; sürdürülebilirlik, atık minimizasyonu ve katma değer oluşturma açısından da önemli bir strateji olarak öne çıkmaktadır (Rosales vd., 2023).

7. Sonuç Ve Gelecek Perspektifler

Mevcut literatür, polifenoller ve diğer doğal antioksidanların fonksiyonel gıda sistemlerinde etkin kullanılabilmesi için mikroenkapsülasyonun giderek zorunlu hâle gelen bir teknoloji olduğunu göstermektedir (Bińkowska vd., 2024; Mehta vd., 2022). Mikroenkapsülasyon;

- ısı, oksijen, ışık ve pH gibi stres faktörlerine karşı fizikokimyasal stabiliteyi artırmakta,
- sindirim sistemi boyunca biyoerişilebilirlik ve biyoyararlanımı iyileştirmekte,

- istenmeyen tat ve koku gibi duyusal kısıtları azaltmakta,
- toz formda, ısıl işleme dayanıklı ve formülasyona uygun taşıyıcı bileşenler geliştirilmesine olanak vermektedir (Santos vd., 2020).

Sprey kurutma ve dondurarak kurutma, endüstriyel uygulamalar açısından hâlen en yaygın yöntemler olmakla birlikte; kompleks koaservasyon, nanoemülsiyon ve lipozomal sistemler gibi daha gelişmiş yaklaşımlar, hedefli salım ve kontrollü etki açısından önemli fırsatlar sunmaktadır (Mehta vd., 2022). Duvar materyali olarak maltodekstrin, gum arabik, modifiye nişasta, inülin, whey proteini ve bitkisel proteinlerin tek başına veya kombinasyon hâlinde kullanılması, kapsül verimi ve fenolik stabilitesi üzerinde belirleyici olmaya devam etmektedir (Santos vd., 2020; Karrar vd., 2021). Gelecekte, mikroenkapsülasyonun çok bileşenli fonksiyonel gıdalar (örneğin polifenol + probiyotik + omega-3 kombinasyonları), kişiselleştirilmiş beslenme yaklaşımları ve endüstri yan ürünlerinin yüksek katma değerli bileşenlere dönüştürülmesinde daha da kritik bir rol üstleneceği öngörülebilir (Ordóñez-García vd., 2024).

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BIOCONTROL POTENTIAL OF *CLONOSTACHYS ROSEA* ISOLATES AGAINST SELECTED SOIL-BORNE FUNGAL PATHOGENS OF LETTUCE

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ABSTRACT

Biological control agents play an increasingly important role in sustainable plant disease management. In this study, the in vitro antagonistic efficacy of three isolates of *Clonostachys rosea* (CR11, CR14, CR15) was evaluated against soil-borne fungal pathogens of lettuce (*Lactuca sativa*), namely *Fusarium oxysporum* f. sp. *lactucae*, *Sclerotinia sclerotiorum*, and *S. minor*, which cause significant economic losses in lettuce production. Experiments were conducted using the dual culture method, wherein the radial growth of pathogenic colonies was measured and inhibition rates were calculated. Results demonstrated that all *C. rosea* isolates exhibited antagonistic activity against the tested pathogens. The highest inhibition was observed against *F. oxysporum* f. sp. *lactucae*, with CR11, CR14, and CR15 isolates providing inhibition rates of 48.7%, 50.99%, and 50.20%, respectively. Moderate efficacy was recorded against *S. sclerotiorum* (CR11: 43.7%, CR14: 40.82%, CR15: 39.11%), while the lowest inhibition was detected against *S. minor* (CR11: 31.5%, CR14: 26.0%, CR15: 28.7%). Notably, the CR14 isolate completely suppressed sclerotia formation in *S. sclerotiorum*, a significant finding for long-term disease management. Additionally, in dual culture assays, distinct pigmentation changes were observed in *Sclerotinia* colonies at interaction zones with *C. rosea*, suggesting that pathogenic hyphae experienced physiological stress. These findings suggest that *C. rosea* acts through multiple antagonistic mechanisms including mycoparasitism, antifungal metabolite production, and cell wall degradation. The study demonstrates that the CR14 isolate shows considerable promise as an effective biological control agent for lettuce disease management.

Keywords: *Clonostachys rosea*, biological control, lettuce soil-borne diseases

1.GİRİŞ

Sürdürülebilir bitki sağlığı, artan gıda ihtiyaçlarını karşılayan verimliliğin, ekosistem korunmasıyla dengelenmesini gerektirmektedir (Rockström ve ark., 2017). Kimyasal pestisitlere dayalı tek başına stratejiler, patojen direnci, toprak mikrobiyotası üzerindeki baskı ve artan mevzuat kısıtlamaları nedeniyle yetersiz kalmaktadır (Hawkins ve ark., 2019; Swaine ve ark., 2025). Bu sınırlamalar, entegre hastalık yönetiminde biyolojik mücadeleyi, kimyasal yaklaşımları tamamlayan önemli bir strateji olarak öne çıkarmaktadır (He ve ark., 2021; Collinge ve ark., 2022). Biyolojik mücadele ajanlarının stratejik değeri, ekosistemi korumaları ve farklı tarımsal uygulamalara destek olmaları ile yerel koşullara adatasyon yeteneğiyle önem kazanmaktadır (Sentis ve ark., 2022; Wyckhuys ve ark., 2024). Bu çerçevede, farklı etki mekanizmalarına sahip ve çok yönlü uygulama potansiyeli sunan biyolojik mücadele ajanlarının rolü daha da ön plana çıkmaktadır. Bu ajanlar arasında, *Clonostachys rosea* özellikle dikkat çekmekte; mikoparazitizm, antibiosis, rekabet ve hücre duvarı parçalayıcı enzim üretimi gibi çoklu biyokontrol mekanizmaları ile çok sayıda fungal patojen, nematod ve toprak kökenli hastalık etmenine karşı geniş spektrumlu etkinliği sayesinde sürdürülebilir bitki hastalık yönetiminde önemli bir alternatif oluşturmaktadır (Sun ve ark., 2020; Hasan ve ark., 2022; Geiger ve ark., 2022).

Biyolojik mücadele ajanlarının uygulanması, özellikle toprak kökenli patojenlerden kaynaklı ciddi kayıpların yaşandığı yaprağı yenen sebzelerin üretiminde büyük önem taşımaktadır (Shinde ve ark., 2011; Gilardi ve ark., 2018; Carlucci ve ark., 2023). Marul (*Lactuca sativa* L.), dünya genelinde yaygın olarak üretilen ve taze tüketimi tercih edilen ekonomik açıdan önemli bir yaprağı yenen sebzedir (Gargaro ve ark., 2023; Křístková ve ark., 2008). Ancak, beyaz çürüklük hastalığına neden olan *Sclerotinia sclerotiorum* ve *S. minor* ile Fusarium solgunluğuna yol açan *Fusarium oxysporum* f. sp. *lactucae* gibi toprak kökenli fungal patojenler marul üretiminde ciddi verim kayıplarına ve kalite düşüşüne neden olmaktadır (O'Sullivan ve ark., 2021; Clarkson ve ark., 2014; Canpolat ve Tülek, 2019; Mestdagh ve ark., 2023). Bu patojenlerin kontrolünde kimyasal fungisitlerin etkinliği, uygulama zamanlaması ve çevresel koşullara bağlı olarak sınırlı ve değişken olup (O'Sullivan ve ark., 2021; Mueller ve ark., 2002), yoğun kullanım ise çevre ve insan sağlığı açısından riskler taşırken fungisit direncinin gelişimine neden olmaktadır (Naqvi ve ark., 2025; El-Aswad ve ark., 2023).

Bu bağlamda, mevcut çalışma, *C. rosea* izolatlarının *S. sclerotiorum*, *S. minor* ve *F. oxysporum* f. sp. *lactucae* üzerindeki in vitro antagonistik etkinliğini değerlendirmeyi amaçlamaktadır.

2. MATERYAL VE METOT

2.1. Materyal

Bu çalışmada, biyolojik mücadele ajanı olarak Zirai Mücadele Merkez Araştırma Enstitüsü kültür koleksiyonundan temin edilen *C. rosea*' nın üç farklı suşu (CR11, CR14 ve CR15) kullanılmıştır. Patojen olarak kullanılan *F. oxysporum* f. sp. *lactucae*, *S. sclerotiorum* ve *S. minor* izolatları ise daha önce maruldan (*L. sativa*) izole edilmiş ve patojenisite testleri yapılarak Sivas Bilim ve Teknoloji Üniversitesi Tarım Bilimleri ve Teknolojileri Fakültesi Bitki Koruma Bölümü kültür koleksiyonunda muhafaza edilmiştir.

2.2. Metot

C. rosea' nın *F. oxysporum* f. sp. *lactucae*, *S. sclerotiorum* ve *S. minor*' a karşı antagonistik aktivitesi, ikili kültür (dual culture) yöntemi kullanılarak değerlendirilmiştir (Dennis ve Webster, 1971a; Skidmore ve Dickinson, 1976). Deneme, her patojen için üç tekerrürlü ve bir kontrol grubu olacak şekilde yürütülmüştür. İnokülasyondan önce, *C. rosea* ve patojen

izolatları Patates Dekstroz Agar (PDA) üzerinde 25 ± 2 °C'de yedi gün süreyle ön kültüre alınmıştır (Geiger ve ark., 2022; Dennis ve Webster, 1971a,b; Skidmore ve Dickinson, 1976). İnokülasyon, 5 mm çapında aktif olarak büyüyen misel disklerinin, 9 cm çaplı PDA içeren Petri kaplarının kenarından 1 cm uzağa, karşılıklı taraflara yerleştirilmesiyle gerçekleştirilmiştir. Kontrol Petri kaplarına sadece patojen misel diskleri yerleştirilirken, uygulama gruplarında patojen ve *C. rosea* misel diskleri karşılıklı olarak yerleştirilmiştir (Flores-Bazauri ve ark., 2015; Rodríguez ve ark., 2015). Uygulamayı takiben, tüm Petri kapları 25 ± 2 °C sıcaklıkta ve karanlıkta inkübasyona bırakıldıktan sonraki 3., 5., 7. ve 14. günlerde, patojen kolonilerinin merkezden kenara doğru radyal gelişimi ölçülmüştür. Nihai değerlendirme, kontrol gruplarındaki patojen kolonileri Petri kabı yüzeyini tamamen kapladığında (14. gün) yapılmıştır. *C. rosea* tarafından patojen gelişiminin engelleme yüzdesi (%I); (C−T)/C×100 formülü kullanılarak hesaplanmıştır (Skidmore ve Dickinson, 1976; Fokkema, 1973). Burada C, kontrol grubundaki patojenin koloni yarıçapını (mm); T, *C. rosea* ile yapılan uygulamadaki patojenin koloni yarıçapını (mm) ifade etmektedir.

3. BULGULAR

In vitro antagonizma testleri, her üç *C. rosea* izolatının da (CR11, CR14 ve CR15) test edilen üç fitopatojenin miseliyal gelişimini değişen derecelerde engellediğini ortaya koymuştur (Tablo 1).

Tablo 4. *Clonostachys rosea* İzolatlarının Farklı Patojenik Funguslara Karşı Engelleme Oranları *(%)*

Patojen	**CR11 (%)**	**CR14 (%)**	**CR15 (%)**
Fusarium oxysporum* f. sp. *lactucae	48.7	50.99	50.20
Sclerotinia sclerotiorum	43.7	40.82	39.11
Sclerotinia minor	31.5	26.0	28.7

En yüksek antagonistik etki, *F. oxysporum* f. sp. *lactucae*' ye karşı gözlenmiştir. Bu patojene karşı engelleme oranları CR11 için %48.7, CR14 için %50.99 ve CR15 için %50.20 olarak ölçülmüştür; CR14 izolatı bu grupta en yüksek performansı sergilemiştir (Şekil 1-B). *S. sclerotiorum*' a karşı elde edilen engelleme oranları, *F. oxysporum* f. sp. *lactucae*' ye kıyasla daha düşük bir seviyede kalmıştır. Engelleme değerleri %43.7 (CR11), %40.82 (CR14) ve %39.11 (CR15) olarak kaydedilmiştir. Test edilen patojenler arasında en düşük engelleme oranları *S. minor*' a karşı tespit edilmiştir. *S. minor*' un miseliyal gelişimi, CR11 tarafından %31.5, CR14 tarafından %26.0 ve CR15 tarafından %28.7 oranında engellenmiştir (Şekil 1-D). Bu bulgular, test edilen *C. rosea* izolatlarının, *Sclerotinia* türlerine kıyasla *F. oxysporum* f. sp. *lactucae* üzerinde daha güçlü bir antagonistik potansiyele sahip olduğunu ve *S. minor*' un bu biyokontrol ajanlarına karşı en yüksek toleransı gösterdiğini ortaya koymaktadır.



Şekil 13. *In vitro* koşullarda *C. rosea*' nın *F. oxysporum* f. sp. *lactucae* (A-B), *S. minor* ile etkileşimi (C-D)

C. rosea ile yapılan uygulamalarda, *S. sclerotiorum*'un sklerotları, yoğun sporodokiyal yapılar tarafından sıklıkla kolonize edilmiştir (Şekil 2-C, D). Özellikle, CR14 izolatı sklerot gelişiminin tamamen engellenmesini sağlamıştır (Şekil 2-A). Buna karşılık, kontrol uygulamasında, *S. sclerotiorum* sağlıklı ve morfolojik olarak bozulmamış sklerotlar üretmiştir (Şekil 2-B). Bu bulgular, *C. rosea*'nın, miseliyal gelişimi hem baskılayarak hem de *S. sclerotiorum*'da hayatta kalma yapılarının oluşumuna müdahale ederek ikili bir etki gösterdiğini düşündürmektedir. Ayrıca, kontrol gruplarında (Şekil 2-B), bu patojenlerin tipik morfolojik bir özelliği olan homojen ve yoğun beyaz miseliyal gelişim gözlenmiştir. Eş zamanlı olarak, uygulama yapılan Petri kaplarında *S. sclerotiorum* ve *S. minor* kültürde yeşil ve kahverengimsi bir renk değişimi gözlenmiştir (Şekil 1-D, 2-A).



Şekil 14. *In vitro* koşullarda *C. rosea*'nın *S. sclerotiorum* ile etkileşimi

Bu sonuçlar, *C. rosea* izolatlarının, özellikle de CR14'ün, *F. oxypsorum* f. sp. *lactucae'* nin gelişimini önemli ölçüde engelleyebildiğini ve *S. sclerotiorum*'daki sklerotlar gibi kalıcı hayatta kalma yapılarının oluşumunu bozduğunu göstermektedir. Bu bulgu, *C. rosea*'nın önemli biyokontrol potansiyelini vurgulamaktadır.

4. TARTIŞMA VE SONUÇ

Bu çalışmada, üç *C. rosea* izolatının (CR11, CR14, CR15) in vitro koşullarda *F. oxysporum* f. sp. *lactucae*, *S. sclerotiorum* ve *S. minor*'un misel gelişimini farklı düzeylerde engellediği gösterilmiştir. Bu çalışmada test edilen *C. rosea* izolatları, *F. oxysporum* f. sp. *lactucae*'ye karşı *Sclerotinia* türlerine kıyasla daha yüksek antagonistik aktivite sergilemiştir. En yüksek engelleme oranı *F. oxysporum* f. sp. *lactucae*'de (%48.7-50.99) gözlenirken, *S. sclerotiorum*'da orta düzeyde (%39.11-43.7) ve *S. minor*'da ise en düşük (%26.0-31.5) etkinlik tespit edilmiştir.

Önceki çalışmalarla uyumlu şekilde, *C. rosea*'nın *Fusarium* türlerine karşı belirgin antagonistik aktivite gösterdiği bilinmektedir (Sun ve ark., 2020; Nagaraj ve ark., 2023). Nagaraj ve ark. (2023), *C. rosea* izolatlarının in vitro ortamda *F. oxysporum* f. sp. *lycopersici* misel gelişiminde

%59.4 ile %71.6 arasında azalma sağladığını bildirmiştir; bu sonuçlar, mevcut çalışmada elde edilen %48.7-50.99 inhibisyon oranlarıyla karşılaştırılabilir düzeydedir. Son yıllarda yapılan genomik, transkriptomik ve metabolomik analizler içeren karşılaştırmalı omik çalışmalar, örneğin *F. graminearum* ile etkileşimde, *C. rosea*'nın hücre duvarı parçalayıcı enzimler (CWDE'ler), ikincil metabolitler ve taşıyıcı proteinler gibi çoklu moleküler mekanizmalarla antagonistik yanıt verdiğini ortaya koymuştur (Demissie ve ark., 2020; Sun ve ark., 2020; Bahadoor ve ark., 2023).

Öte yandan fonksiyonel genetik çalışmalar, *S. sclerotiorum*'a karşı mikoparazitizmde Chi67-1 gibi kitinaz genlerinin önemli rol oynadığını göstermiştir. Chi67-1 geni aşırı eksprese edilen *C. rosea* transformantlarının önemli bir kısmında, *S. sclerotiorum* sklerotlarına karşı parazitlenme oranının yaklaşık %50 daha yüksek olduğu ve en iyi transformantta kitinaz aktivitesinin 2,4 kat arttığı belirlenmiştir (Sun ve ark., 2015, 2017). Bu bulgular, *F. oxysporum*'un hücre duvarı bileşenlerine yönelik enzimatik degradasyonun, *C. rosea*'nın yüksek antagonistik etkinliğinde rol oynayan temel mekanizmalardan biri olabileceğini düşündürmektedir (Sun ve ark., 2020).

S. sclerotiorum açısından ise, elde edilen inhibisyon oranları (%39.11-43.7) *Fusarium* türlerine kıyasla daha düşük olmakla birlikte, anlamlı antagonistik etkinlik düzeyindedir. Özellikle dikkat çeken bir bulgu, CR14 izolatının *S. sclerotiorum*'un sklerot üretimini tamamen baskılamış olmasıdır. Sklerotlar, toprak kökenli patojenlerin uzun vadede canlılığını sürdürmesini sağlayan ve tarla koşullarında hastalık salgınlarının tekrarlamasında kritik rol oynayan kalıcı inokulum kaynaklarıdır (Purdy, 1979; Smolińska ve Kowalska, 2018). Rodríguez ve ark. (2011), *C. rosea*'nın sklerotları yoğun bir şekilde kolonize ederek canlılıklarını önemli ölçüde azalttığını bildirmiştir. Mevcut çalışmada da CR14 uygulamasında sklerotların gelişemediği veya gelişse bile fiziksel temas ile bu yapıların kolaylıkla parçalandığı ve morfolojik olarak bozulmuş yapılar sergilediği gözlemlenmiştir. Bu bulgu, *C. rosea*'nın sadece misel gelişimini baskılamakla kalmayıp, sklerot canlılığını düşürerek toprak inokulum yoğunluğunu azaltma potansiyeline sahip olduğunu göstermektedir.

Dual kültür testlerinde, *S. sclerotiorum* ve *S. minor* kolonilerinde, *C. rosea*'ya yakın bölgelerde tipik beyaz kolonilerden yeşilimsi-kahverengiye dönüşen belirgin bir pigmentasyon değişimi gözlenmiştir. Kontrol gruplarında bu renk değişimi görülmemiştir. Bu gözlem, *C. rosea* ile etkileşim bölgesindeki patojen hiflerinin fizyolojik stres altında olduğunu düşündürmektedir. Benzer şekilde, son çalışmalarda antagonistik etkileşimler sırasında patojen hiflerinde pigment birikiminin ve oksidatif stres göstergelerinin (örneğin ROS birikimi, melanizasyon) arttığı bildirilmiştir (Butler ve ark., 2009; Liang ve ark., 2018; Ayaz ve ark., 2024). Bu bulgular, *C. rosea'*nın çok yönlü antagonistik mekanizmalarının (doğrudan mikoparazitizm, antifungal metabolit üretimi, hücre duvarı degradasyonu) birlikte etki gösterdiğini desteklemektedir (Sun ve ark., 2020).

Mevcut çalışmada, *S. minor* üzerinde elde edilen inhibisyon oranlarının (%26.0-31.5) hem *F. oxysporum* hem de *S. sclerotiorum*'a kıyasla önemli ölçüde düşük olması dikkat çekicidir. Literatürde, Sclerotinia türlerinin biyolojik kontrol ajanlarına karşı hassasiyetlerinin, popülasyonlar ve izolatlar arasında değişkenlik gösterebildiği rapor edilmiştir (Nicot ve ark., 2019; Smolińska ve Kowalska, 2018). Sclerotinia türlerinde oksalik asit üretiminin patojeniteyle yakın ilişkili olduğu ve bazı *S. minor* izolatlarının da yüksek düzeyde oksalik asit üretebildiği bildirilmiştir; ancak oksalik asit miktarları hem türler hem de izolatlar arasında geniş varyasyon göstermektedir (Mihajlović ve ark., 2024; Bolton ve ark., 2006). Sclerotinia türlerinde sklerotial melanin, UV ışığı, sıcaklık dalgalanmaları ve diğer çevresel streslere karşı dayanıklılığı artıran; dolayısıyla sklerotların mikrobiyal antagonistler ve biyolojik kontrol etmenleri tarafından kolonize edilmesini güçleştirebilen önemli bir koruyucu faktör olarak

değerlendirilmektedir (Butler ve ark., 2009; Ordóñez-Valencia ve ark., 2015; Bolton ve ark., 2006; Chitrampalam ve ark., 2011; Rabeendran ve ark., 2006). *S. minor*'ın küçük ve yoğun melanize sklerotlarının, rind tabakasının histolojik organizasyonunun ve sklerotların farklı gelişim aşamalarındaki duyarlılıklarının da biyolojik kontrol ajanlarının penetrasyonunu güçleştirerek antagonistik etkinliği sınırlayabileceği öne sürülmektedir (Bullock ve ark., 1980; Rey ve ark., 2005).

Sonuç olarak, *C. rosea* izolatlarının in vitro koşullarda özellikle *F. oxysporum* f. sp. *lactucae*'nin misel gelişimini baskılama ve *S. sclerotiorum*'da sklerot oluşumunu engelleme kapasiteleri, bu türün entegre hastalık yönetimi açısından önemli potansiyel taşıdığını ortaya koymaktadır. CR14 izolatının özellikle sklerot inhibisyonundaki performansı, bu suşun marulda beyaz çürüklük ve Fusarium solgunluk hastalıklarının yönetiminde kullanılabilir bir biyolojik kontrol ajanı olarak geliştirilmesi açısından umut vericidir. Ancak in vitro ortamda elde edilen bu bulguların, sera ve tarla koşullarında gerçekleştirilecek daha kapsamlı araştırmalarla doğrulanması gerekmektedir. Gelecek çalışmalarda, *C. rosea* izolatlarının formülasyon geliştirme, raf ömrü, çevresel koşullara adaptasyon ve tarla koşullarında etkinliği üzerine odaklanılması, bu biyokontrol ajanının ticari uygulamalarının yaygınlaşmasına katkı sağlayacaktır.

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PLANT PARASITIC NEMATODES CAUSING DAMAGE IN ORNAMENTAL PLANTS

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ABSTRACT

Ornamental plant cultivation is a rapidly growing agricultural sector worldwide, with the market expected to reach $50 billion in 2025. Root-knot nematodes (RKN), root lesion nematodes, and viral vector nematodes are major pests causing significant yield and quality losses in ornamental plant production. Plant-parasitic nematodes (PPN) account for approximately 14% of global agricultural losses, with ornamental plants experiencing around 11% loss due to nematode infestation. *Meloidogyne* spp. (root-knot nematodes), *Aphelenchoides* spp. (foliar nematodes), *Ditylenchus dipsaci* (stem and bulb nematode), and viral vector nematodes such as *Xiphinema*, *Longidorus*, *Trichodorus*, and *Paratrichodorus* are among the most common damaging species in ornamental crops. Root-knot nematodes cause galling in roots, foliar nematodes produce necrotic lesions on leaves, stem and bulb nematodes induce rot in bulbs and stems, while viral vector nematodes transmit diseases causing mosaic, ring spot, and necrosis symptoms. Studies conducted in Turkey on important cut flowers such as gerbera, carnation, and roses have revealed the widespread occurrence of various nematode species. Traditional control methods include hot water treatment, soil fumigation, and nematicide application; however, environmental and economic concerns have led to the banning of many effective fumigants and nematicides, necessitating the development of alternative management strategies. The use of resistant varieties, biological control, and integrated pest management approaches have become critical for ensuring sustainable and profitable ornamental plant production.

Keywords: Plant-parasitic nematodes, Ornamental plants, Nematode management

1.GİRİŞ

Süs bitkileri yetiştiriciliği, dünya genelinde hızla gelişen ve milyarlarca dolarlık ticaret hacmine sahip bir tarımsal üretim koludur. Bu sektör; peyzaj düzenlemeleri, iç ve dış mekân bitkilendirme uygulamaları, çevre estetiği ve yeşil alan tasarımı gibi çok çeşitli kullanım alanlarına sahiptir (Salachna, 2022). Son yıllarda çiçek ve süs bitkileri pazarı önemli ölçüde büyüme göstermiş olup 2024 yılında 46,31 milyar dolar olan pazar büyüklüğünün 2025 yılında %8,4'lük büyüme oranı ile 50,17 milyar dolara ulaşacağı öngörülmektedir (Anonymous, 2025). Bu ekonomik büyüme, süs bitkileri üretiminin istihdam yaratma ve kırsal kalkınmaya katkı sağlama potansiyelini de artırmaktadır (Martinho, 2012).

Süs bitkileri üretiminde verim ve kaliteyi olumsuz etkileyen başlıca kısıtlayıcı unsurlar arasında biyotik ve abiyotik stres faktörleri önemli bir yer tutmaktadır. Sıcaklık ekstremleri, su stresi ve besin yetersizlikleri gibi abiyotik etmenler ile virüsler, bakteriler, funguslar, böcekler ve nematodlar gibi biyotik etmenler bitkilerin gelişimini sınırlamaktadır (Lal ve ark., 2023). Bu biyotik stres unsurları arasında, çoğu toprak kökenli mikroskobik olan ve zararı çoğu zaman fark edilmeden ilerleyen bitki paraziti nematodlar (BPN), süs bitkileri üretiminde önemli ekonomik kayıplara neden olmaktadırlar. Özellikle kök sistemine zarar vererek bitkinin su ve besin alımını engelleyen BPN'ler, üretim sürecinde dikkate alınması gereken başlıca zararlılardan biridir (Howland ve Quintanilla, 2023).

Bitki paraziti nematodlar (BPN), tarımı yapılan bitki türlerinin tamamında zarar yapabilmeleri ve yabancı otların büyük kısmını enfekte edebilmeleri nedeniyle tarımsal üretimdeki en büyük tehditlerden biri durumundadır. Amerikan Fitopatoloji Derneği'ne (APS) göre, küresel ölçekte tarımsal verim kayıplarının %14'ü BPN'lardan kaynaklanırken bunun yıllık maddi karşılığının yaklaşık 125 milyar dolar olduğu tahmin edilmektedir (Chitwood, 2003). Nematodlardan kaynaklanan ekonomik kayıplarda BPN türünün virülensi ve coğrafi dağılımı ile bitkisel ürünün ekonomik değeri etkili olmaktadır. Dünyada en çok zarara neden olan nematod türünün konukçu spektrumu çok geniş olan kök ur nematodları (*Meloidogyne* spp.) olduğu ve bunu sırasıyla kist nematodları (*Heterodera* ve *Globodera* spp.), kök lezyon nematodları (*Pratylenchus* spp.), kök oyucu nematod (*Radopholus similis*) ve soğan sak nematodu (*Ditylenchus dipsaci*)'nun izlediği bildirilmiştir (Jones ve ark., 2013). Mücadele yapılmayan alanlarda kök ur nematodları %100 e varan kayıplara neden olurken, kist nematodları ve kök ur nematodlarının birçok ülkede ortalama % 90'lara varan hasarlara neden olduğu (Meagher, 1972; Maqbool ve Zarina, 1988; Nicol ve ark., 2011) soğan sak nematodunun ise %80'e kadar zarar verdiği tespit edilmiştir (Sturhan ve Brzeski, 1991).

BPN'ler sebzeler, meyveler, çiçek ve süs bitkileri, baharat ve çeşniler, tıbbi ve aromatik bitkiler ve yumrulu bitkiler gibi başlıca bahçe bitkilerinde ciddi şekilde zarar yapmakta olup bu çok değerli ürünlerin birçoğunda verimin azalmasına ve hatta ölümüne neden olmaktadırlar (Ravichandra, 2014). Yapılan çalışmalar sonucunda bahçe bitkilerindeki BPN kaynaklı verim kaybının yaklaşık %13,5 süs bitkilerindeki kaybın ise %11,1 olduğu tahmin edilmektedir (Ravichandra, 2014). Tarımsal üretim üzerinde böylesine önemli bir etkiye sahip olan BPN'nin yaygınlığı, zarar seviyeleri ve mücadele olanakları üzerine birçok çalışma yapılmasına karşın dünya genelinde yaklaşık 70 milyar dolarlık bir endüstri olan süs bitkileri ile ilgili olarak yapılan çalışmalar daha sınırlı düzeydedir (Madhavan ve ark., 2021). Son yapılan araştırmalara göre süs bitkilerinde Dünya genelinde sorun oluşturan bitki paraziti nematodlar; *Meloidogyne* spp., *Ditylenchus* spp., *Aphelenchoides* spp., *Paratylenchus* spp., *Pratylenchus* spp., *Helicotylenchus* spp., *Radopholus* spp., *Xiphinema* spp., *Trichodorus* spp., *Paratrichodorus* spp., *Rotylenchulus* spp. ve *Longidorus* spp. olarak bildirilmiştir (Howland ve Quintanilla, 2023). *Ditylenchus* ve *Aphelenchoides* cinslerinin özellikle soğan ve yaprak parazitleri olarak;

Meloidogyne, *Radopholus*, *Pratylenchus*, *Heterodera*, *Xiphinema*, *Longidorus*, *Paratrichodorus*, *Criconemoides*, *Belonolaimus* ve *Hoplolaimus* spp. cinslerinin ise kök parazitleri olarak ekonomik anlamda zarar yapan türleri içerdiği bildirilmiştir (Bridge ve Starr, 2007).

Bu durum Türkiye açısından değerlendirildiğinde de benzer bir durum görülmektedir. Yüksel (1974) tarafından İstanbul'da begonyada *Meloidogyne hapla*'nın tespit edildiği çalışma süs bitkilerindeki ilk çalışma durumundadır. Antalya ili Gerbaera (*Gerbera jamesonii* L.) ve Karanfil (*Dianthus caryophyllus* L.) yetiştirilen alanlarda yürütülen çalışma sonucunda *Meloidogyne* spp., *Helicotylenchus* spp., *Aphelencoides* spp., *Xiphinema* spp., *Pratylenchus* spp., *Longidorus* spp. yaygınlıkları sırasıyla %21,02, 10,24, 4,05, %0,06, %0,44 ve 0,01 olarak belirlenmiştir. Aynı çalışmada üç farklı gerbera çeşidinde *M. incognita* üreme oranının 1,9 ila 2,7 arasında değiştiği, 14 farklı karanfil çeşidinde ise üç çeşitte üreme görülmezken diğer çeşitlerde ise üreme oranının 0,8 ila 3,9 arasında değiştiği ve ayrıca *A. besseyi* zararı sonucunda gerbera çeşitlerinde %20 ila %40 arasında değişen oranlarda bitki ölümü görüldüğü bildirilmiştir (Yarba, 2019). Antalya ili örtü altı alanlarda yapılan çalışmada ise karanfil, gerbera ve lisyantus kesme çiçeklerinde yapılan çalışma sonucunda *Pratylenchus thornei, P. neglectus, Meloidogyne incognita, M. javanica, M. arenaria* ve *M. hapla* yaygınlığı sırasıyla %98,73, %88,60, %65,82, %34,17, %22,78 ve %5,06 olarak belirlenmiştir (Sert Çelik ve ark., 2019). Yalova ili sera alanlarında yetiştiriciliği yapılan 6 farklı kesme çiçek çeşidi gül, şebboy, krizantem, hüsnü yusuf, Lisianthus ve frezyada zarar yapan bitki paraziti nematodların tespit edildiği çalışma sonucunda *Meliodogyne incognita, M. hapla, Aphelenchus avenae, Aphelenchoides* sp., *Trophurus imperialis, Longidorus moesicus, Pratylenchus vulnus, Paratylenchus hamatus, Rotylenchus arasbaranensis* türleri tespit edilmiştir (Çelik, 2019). Dört farklı karanfil çeşidinin kök-ur nematodlarına dayanıklılık durumlarının araştırıldığı çalışmada ise *Meloidogyne incognita, M. javanica* ve *M. arenaria* türlerine Turbo çeşidinin dayanıklı, Betsy ve Glaciar çeşitlerinin hassas, Nirvana çeşidinin ise *M. incognita, M. javanica*'ya orta dayanıklı *M. arenaria*'ya ise tam dayanıklı olduğu belirlenmiştir (Sert Çelik ve ark., 2022).

2. NEMATODLARIN ZARAR VERDİĞİ BAŞLICA SÜS BİTKİLERİ

Krosandra, sümbülteber, krizantem, gül, yasemin, orkide, glayöl, karanfil, gerbera, antoryum, zambak, kadife çiçeği ve aster gibi türler, yaygın olarak yetiştirilen başlıca geleneksel ve ticari süs bitkileri arasında yer almaktadır. Dünya genelinde birçok nematod türünün çeşitli süs bitkileriyle ilişkili olduğu bildirilmiş olsa da (Tablo 1), bazı bitkiler üzerinde yapılan çalışmalar halen yetersizdir. Çiçekçiliğin dünya genelinde büyük bir endüstri haline gelmesiyle birlikte, nematodlar süs bitkileri de dahil olmak üzere sera ve tarla koşullarında yetiştirilen ürünlerdeki en önemli üretim kısıtlarından biri haline gelmiştir. (Ravichandra, 2014).

Tablo 1. Önemli süs bitkilerinde zarar yapan başlıca bitki paraziti nematod türleri (Ravichandra, 2014)

Bitki	**Nematod**
Çiçekli bitkiler	
Asparagus sprengeri	*Helicotylenchus cavenessi*
Asterler	*Aphelenchoides ritzemabosi*
Begonya	*Meloidogyne incognita*
Cineraria hybrida	*Helicotylenchus* spp.
Karanfil	*R. reniformis, M. Arenaria, M. Hapla, M. Javanica, M. İncognita, Ditylenchus dipsaci, Heterodera trifolii, Criconemella curvata, Pratylenchus dianthus, Paratylenchus curvitatus, Tylenchus, Macroposthonia curvata*
Krizantem	*Aphelenchoides ritzemabosi, Helicotylenchus* sp., *Meloidogyne* spp., *Pratylenchus penetrans, R. reniformis*
Crossandra	*M. incognita, Pratylenchus delattrei, P. africans*
Dahlia	*A. ritzenabosi, Ditylenchus destructor*
Glayöl	*Meloidogyne* spp., *Helicotylenchus rotundicaudatus, Scutellonema brachyurum,*
Hemerocallis	*H. rotundicaudatus*
Hibiscus rosa-sinensis	*Helicotylenchus varicaudatus*
Sümbül ve Lale	*Ditylenchus*
Yasemin	*M. incognita, A. besseyi*
Zambak	*Pratylenchus penetrans*
Orkideler	*A. ritzemabosi*
Phlox	*X. vuittenezi*
Gül	*Pratylenchus vulnus, M. Hapla, Helicotylenchus labiata, H. Dihystera, H. 1942anus, Hoplolaimus galeatus, X. Diversicaudatum, Pratylenchus penetrans, Hemicycliophora typical, Longidorus macrosoma*
Ada çayı	*A. ritzemabosi*
Zinnia elegans	*A. ritzemabosi*
Eğrelti otları	
Asplenium nidus	*A. ritzemabosi*
Aucuba japonica	*M. arenaria*
Buxus microphylla	*M. arenaria*
B. sempervirens	*M. arenaria, Pratylenchus vulnus, Criconemella xenoplax*
Camellia japonica	*Tylenchorhynchus claytoni*
Gardenia jasminoides	*M. arenaria*
Ilex cornuta	*C. xenoplax, T. Claytoni*
I. crenata compacta	*M. arenaria*
Juniperus conferta	*Criconemella xenoplax*
J. excelsa	*Pratylenchus vulnus*
J. horizontalis	*P. vulnus*
Photinia ve *Rhododendron indicum*	*T. claytoni*
Struthiopteris orientalis	*M. arenaria*
Tuberose	*M.*spp.
Odunsu bitkiler	
Abenda grandiflora	*M. hapla*
Kaktüs	*M. incognita, Cactodera cacti, Heterodera cacti*
Cornus florida	*M. hapla*
Croton	*H. cacti*
Ctenatha	*Helicotylenchus dihystera*
Ficus elastica	*Pratylenchus coffeae*
Hippeastrum vittatum	*Pratylenchus coffeae*
Hoya carnosa	*Scutellonema brachyurus*
Momordica	*P. coffeae*
Palmiye	*Helicotylenchus dihystera*

2.1. Süs Bitkilerinde Bitki Paraziti Nematodların Toprak Üstü Belirtileri

Bitki paraziti nematodların zararı sonucunda türe bağlı olarak değişmekle beraber genellikle bitki gelişiminde gerileme, yoğun bulaşıklıklarda arazinin belli yerlerinde çökmeler, gövdelerde deformasyon ve incelme ve yüzey solgunluğu, ısıya karşı olağandışı hassasiyet, yapraklarda sararma, kızarıklık ve yaprak dökülmesi, yavaş büyüme ve erken solma (su stresi) gibi belirtiler arazi içerisinde düzensiz desenler halinde kendini gösterir. Ayrıca, odunsu süs bitkilerinde yaprak dökülmesi ve dallarda yaprak kaybı da gözlemlenebilir (Sigariova ve Karpliyk, 2015; Ravichandra, 2014). Bu semptomlar spesifik değildir ve toprağın düşük verimliliği, bitki besin maddesi eksikliği, kuraklık veya aşırı nem gibi abiyotik faktörlerden kaynaklanabileceği gibi böcekler, viruslar, funguslar veya bakteriler gibi biyotik faktörlerden de kaynaklanabilir (Hubin, 2013; Kiryanova ve Krall, 1969; Matveeva, 1989).

2.2. Süs Bitkilerinde Nematod Hasarının Toprak Altı Belirtileri

Bitki paraziti nematodların süs bitkilerinde toprak altı aksamda oluşturduğu zararlar genellikle hücre ve dokuların mekanik olarak deformasyona uğraması ve bunun sonucu olarak bitkide fizyolojik süreçlerin bozulması, fungal ve bakteriyel patojenlere giriş kapısı oluşturmaları, virüs vektörü nematodların sağlıklı bitkilere virüs bulaştırması sonucunda viral enfeksiyonların yayılması ve bitkinin mikotik funguslarla olan simbiyotik ilişkilerinin bozulması gibi çeşitli şekillerde ortaya çıkar (Hubin, 2013). Bitki paraziti nematodların bir kısmı yaşamlarını toprakta sürdürürken, bazıları ise doğrudan bitki dokularının içinde hareketli veya sabit olarak bulunurlar. Örneğin, *Pratylenchus* cinsi süs bitkilerinin kök dokularında hareketli endoparazit olarak zarar yaparken *Ditylenchus* cinsi ise soğan, gövde ve yapraklarda hareketli endoparazit olarak zarar yapmaktadırlar. *Meloidogyne* ve *Heterodera* cinslerinde yer alan türler ise sabit endoparazit olarak sınıflandırılır ve bu türler yaşam çemberlerinin büyük kısmını kök içinde sabit olarak geçirirler. Öte yandan, *Rotylenchus, Tylenchorhynchus, Helicotylenchus* ve *Paratylenchus* gibi cinslerde yer alan türler ise toprakta yaşayan ve kök sistemindeki hücre içeriklerini emerek beslenen ektoparazit nematodlar arasında yer alırlar (Sigariova ve Karpliyk, 2015).

Endoparazitik nematodlar, konukçu bitki dokuları içinde hareket ederken mekanik zarara yol açar; bu durum dokularda tahribata, nekrotik lekelere ve bireysel hücre ölümlerine neden olur (Kiryanova ve Krall, 1969). Ayrıca, nematodların salgıladığı sindirim enzimleri bitki dokularını parçalayarak metabolik aktivitelerin ve homeostazın bozulmasına yol açar. Bu etkiler, bitkinin hasar gören dokularında büyüme ve gelişme geriliği, kök, gövde ve yaprak deformasyonları ile sonuçlanabilir. Şiddetli durumlarda ise bitkinin bazı bölümlerinin tamamen işlevini yitirmesi ya da bitkinin ölümü söz konusu olabilir. Genellikle tomurcuk oluşumu gecikir, çiçeklenme süreci bozulur; bazı çiçekler deforme olurken sayılarında da azalma gözlenir. Bu durum, özellikle çiçekli süs bitkilerinde, ürün kalitesini ciddi şekilde düşürür ve ticari açıdan istenmeyen sonuçlara yol açar (Sigariova ve Karpliyk, 2015).

Diğer birçok kültür bitkisinde olduğu gibi süs bitkileri açısından en türlerin başında gelen kök ur nematodlarının beslenmeleri sonucunda oluşan dev hücreler nedeniyle bitki köklerinde popülasyon yoğunluğuna, türe ve konukçuya bağlı olarak değişen şekil ve büyüklüklerde urlanmalar meydana gelmektedir. Çimen ve birçok süs bitkisinde zarar yapan *Belonolaimus longicaudatus, Paratrichodorus minör* ve *Dolichodorus* spp. ise kök uçlarında zarar yaparak uçları deforme ederler (Şekil 1). *Radopholus similis, Pratylenchus* spp., *Hoplolaimus* spp. zararı sonucunda ise köklerde renk değişimleri görülürken nematodun beslenmesi ve bunun sonucu olarak oluşan yaralanmaların fungal veya bakteriyel etmenlerin zararına imkan vermesiyle kök dokularının yumaşaması ve kararması gibi belirtiler de oluşur (Ravichandra, 2014).



Şekil 1. *Belonolaimus longicaudatus* tarafından zarar gören ve görmeyen bermuda çim alanı ve kökleri

3. SÜS BİTKİLERİNDE GÖRÜLEN ÖNEMLİ BİTKİ PARAZİTİ NEMATODLAR

3.1.Kök-ur Nematodları (*Meloidogyne* spp.)

Bütün dünyada dağılım gösteren, geniş konukçu dizisine sahip obligat parazitler olan kök-ur nematodları (*Meloidogyne* spp.) (KUN) bilimsel ve ekonomik önemleri açısından en çok zarar yapan 10 bitki paraziti arasında ilk sırayı almaktadır (Jones ve ark., 2013). Bitkilerin köklerinde irili-ufaklı ur oluşturmaları ile tanınabilen kök-ur nematodlarının 5500'den fazla konukçusu olduğu bilinmekte olup neredeyse her tarımsal üründe ve çoğu yabancı ot türünde zarar yapabilmektedirler (Hussey ve Janssen, 2002; Elling, 2013; Trudgill ve Blok, 2001). Konukçu bitkilerin köklerinde sabit endoparazit olan kök-ur nematodlarının zararı soncu oluşan dev hücreler nedeniyle köklerde urlanmalar oluşturmaktadırlar (Şekil 2). Özellikle sulama imkânının olduğu sıcak bölgelerde, sebze ve meyve üretimi yapılan alanlarda daha zararlı olan KUN'ları Akdeniz havzasında zarar yapan önemli zararlıların başında gelmekte olup domates ve patates gibi ürünlerde %25 ila %100 arasında değişen oranlarda zarar yapabilmektedir (Conceição ve ark., 2009, Boydston ve ark., 2007). Kök-ur nematodları, dünya genelinde yaklaşık olarak yıllık % 5'lik bir verim kaybına neden olmaktadır ve bitki paraziti nematodlardan kaynaklanan yıllık yaklaşık 100 milyar € maddi kaybın büyük kısmını oluşturmaktadırlar (Abad ve ark., 2003; Agrios, 2005; Sasser ve Freckman, 1987). Kök-ur nematodlarının doğrudan zararları yanında, köke girerken açtıkları yaralardan mikroorganizmaların girişine imkan sağlamaları ile dolaylı zararlara da neden olmaktadırlar (Stirling, 1991).



Şekil 2. Kök-ur nematodunun Lisianthus köklerindeki urlanmalar (McGovern, 2018)

Dünya'da 2020 yılına kadar *Meloidogyne* cinsine ait toplam 105 tür tespit edilmiştir (Ghaderi ve Karssen, 2020). Dünyada saptanan KUN'ları içerisinde *M. incognita, M. javanica, M. arenaria, M. chitwoodi, M. fallax* ve *M. hapla* türleri en yaygın türler olup bu cinsin %95'den fazlasını oluşturmaktadır (Adam ve ark., 2007). *Meloidogyne arenaria, M. incognita* ve *M. javanica* sıcak iklimlerde en yaygın türler durumundadır. Soğuk iklimlerde ise, *M. hapla* ve *M. naasi* açık alanda yetiştirilen ürünlerde önemli türler durumundayken, 1990'lardan bu yana *M. chitwoodi* ve *M. fallax* özellikle patates ve sebze üretiminde yaygın hale gelmiştir (Wesemael ve ark., 2011). Türkiye'de bugüne kadar yapılan çalışmalarda farklı bölgelerde ve farklı kültür bitkilerinde *M. arenaria, M. artiellia, M. chitwoodi, M. exigua, M. hapla, M. incognita, M. javanica, M. luci, M. thamesi* olmak üzere toplam 9 tür tespit edilmiştir (Yüksel 1966, Yüksel 1967, Elekçioğlu 1992, Kepenekci ve ark., 2002, Özarslandan ve ark., 2009, Gerič Stare ve ark., 2017; İmren ve ark., 2014).

Kök-ur nematodu türleri arasında, *Meloidogyne hapla*, Amerika Birleşik Devletleri'nin kuzeyinde ve Kanada'da çok yıllık süs bitkilerinin en önemli zararlıları arasında yer alırken (LaMondia, 1996), Amerika Birleşik Devletleri'nin güneyinde ise çeşitli tropikal kök-ur nematodu türleri süs bitkilerini zarar yapmaktadırlar (Brito ve ark., 2010).

Kök-ur nematodu zararı sonucunda oluşan belirtiler arasında köklerde ur oluşumu, kolayca zayıf gelişim gösteren, solan ve bodurlaşan bitkiler, kloroz gibi bitki besin maddesi eksikliklerinde yaygın olan diğer belirtiler yer alır (Şekil 3). Tarlada yetiştirilen çıplak köklü süs bitkilerinde popülasyon yoğunluğuna bağlı olarak önemli ölçüde verim kayıpları görülebilmekte olup %20'nin üzerinde verim kayıpları oluşabilmektedir (Lindberg ve ark., 2018). Kesme yeşillik bitkilerinde, kök-ur nematodu zararı sonucunda yaprakların ve gövdelerin yeniden büyümesi yavaşlayabilmektedir (Baidoo ve ark., 2017). Ayrıca kök-ur nematodu zararı sonucunda oluşan köklerdeki urlanmalar, süs bitkilerinin satışını ve dağıtımını engelleyerek karı daha da azaltabilmektedir. *Meloidogyne javanica*' nın, krizantem bitkilerinin köklerinde urlara, bitkilerde ciddi bir şekilde bodurluğa ve kloroza neden olduğu belirlenmiştir (Agudelo ve ark., 2006). *M. İncognita*' nın, gerberada %31.1'e kadar verim kaybına yol açtığı bildirilmiştir (Manju ve Subramanian, 2015). Nematod enfeksiyonlarının çiçek üretimi üzerinde de olumsuz etkileri olduğu belirlenmiş olup glayölde, *Meloidogyne incognita* enfeksiyonunun şiddetli olduğu durumlarda hiç çiçek oluşmadığı bildirilmiş ayrıca histolojik analizlerde kök dokusunda dev hücre oluşumları ve vasküler doku deformasyonları belirlenmiştir (Assumi ve ark., 2017). Büyük, etli köklere sahip çok yıllık otsu bitkilerde, özellikle düşük popülasyona sahip alanlarda kök-ur nematodu urlanmaları kolayca göze çarpmayabilmekte ve fark edilmesi zor olabilmekte olup bu durum ihracatta karantina zararlısı olmaları nedeniyle sorunlara neden olabilmektedir (Howland ve Quintanilla, 2023).

Mevcut yönetim stratejileri bu önemli zararlıyla mücadelede sınırlıdır ve genellikle nematodları öldürmek için çoğaltım materyallerinin sıcak suya daldırıldığı sıcak su uygulaması (Powell ve Riedel, 1978; Inserra ve ark., 1995; Daughtrey ve Benson, 2005) ve son derece maliyetli ve çevre için toksik olan ekim öncesi toprak fümigasyonundan oluşmaktadır. Toprak fumigasyonu ve nematisitler KUN ile mücadelede en etkili yöntem olmakla beraber gerek Avrupa Birliği gerekse de ülkemiz mevzuatlarında yapılan değişiklikler sonucunda piyasada yaygın olarak kullanılan 1,3-Dichloropropene, Aldicarp, Carbofuran, Cadusafos, Ethoprophos gibi pekçok fumigant ve non-fumigant nematisitin kullanımı yasaklanmıştır (Anonim 2020). Bu durum biyolojik nematisitler ve organik değişiklikler gibi daha az zarar veren mücadele yöntemlerine doğru bir kayma olmasına neden olmuştur (Zasada ve ark., 2010).



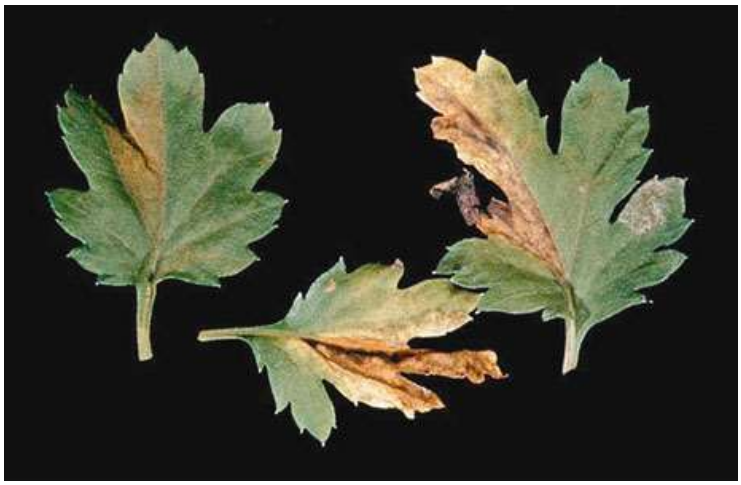
Şekil 3. *Meloidogyne hapla* ile bulaşık (A) ve sağlıklı (B) sarı zambak kökleri (Howland ve Quintanilla, 2023)

3.2.Yaprak Nematodları (*Aphelenchoides* spp.)

Yaprak nematodları, *Aphelenchoides* spp., yıldız çiçeği, orkide ve krizantem gibi birçok süs bitkisi de dahil olmak üzere 700'den fazla bitki türünden oluşan geniş bir konukçu dizisine sahip bitki paraziti nematodlardır (Handoo, 1998; Jagdale ve Grewal, 2006; Kohl, 2011; Mitiku, 2018; Smitamana ve McGovern, 2018). Süs bitkisi endüstrisi için ekonomik öneme sahip üç ana tür *A. fragariae*, *A. ritzemabosi* ve *A. besseyi*'dir. Yaprak nematodları esas olarak yaprakların içinde beslenen endoparazitlerdir, ancak çevresel koşullara bağlı olarak yaprak nematodları bazı bitkilerin yapraklarında ve çiçek tomurcuklarında dıştan da beslenebilirler. Bu nematodlar çoğunlukla toprakta kışı geçirir ve su film tabakası sayesinde bitki gövdelerinin dışından yapraklara doğru göç ederler. Enfekte üretim materyalleri yoluyla kolayca temiz alanlara yayılabilirlerken, yağmur veya sulama suyuyla da yakın mesafedeki temiz bitkilere taşınırlar. Yaprak nematodu beslenmesinden kaynaklanan belirtiler yapraklarda ana yaprak damarlarına paralel uzanan klorotik, köşeli lezyonlardır ve beslenme devam ederse bu belirtiler nekrotik hale gelebilirler (Şekil 4). Bu durum yaprakların kuru, parçalanmış bir görünüme sahip olmasına neden olurken şiddetli enfeksiyonlarda tüm yaprağı öldürerek yaprak dökülmesine neden olabilir (Jagdale ve Grewal, 2006; Kohl, 2011; Mitiku, 2018; Phani ve ark., 2021). *A. subtenuis*'in nergis bitkilerinde neden olduğu enfeksiyonlar, soğanlarda doğrudan zarara, yaprakların erken sararmasına ve verim düşüşüne neden olmaktadır (Chekanai ve ark., 2024). *A. ritzemabosi*, krizantem yapraklarında damarlar arası nekroz, yapraklarda renk değişimi, şekil bozuklukları, sürgün deformasyonları, bodur büyüme ve çiçek veriminde azalma gibi semptomlara neden olmaktadır (Deimi ve ark., 2007). Glayöl bitkilerinin *Aphelenchoides ritzemabosi* ile enfeksiyonu sonucunda damarlar arası nekrotik lekeler, yaprak deformasyonu ve kıvrılması, sürgünlerde zayıf gelişim ve bodurluk, çiçek oluşumunda bozulmalar gözlenmiştir. Bu belirtiler nemli koşullarda daha şiddetli olup, özellikle damarla sınırlı koyu renkli lezyonların tanı için tipik olduğu belirlenmiştir (Basterrechea, 2005). *A. ritzemabosi* ile enfekte olan zambaklarda da yapraklarda sarıdan bronz renge geçiş, kahverengileşme, ancak dökülmeme; gövdede bodurlaşma ve çiçeklenme kaybı, ilerleyen aşamada ise geriye doğru ölme belirtileri gözlenmiştir. Bu da foliar nematodların yapraklarda sistemik yayılım göstererek bitki gelişimini tamamen engelleyebileceğini göstermektedir (Eoun, 1977).

Aphelenchoides türlerinin bulaşık kurumuş yaprak döküntülerinde ve hareketsiz bitki taçlarında

uzun yıllar hayatta kalabilmesi ve temiz alanlara kolaylıkla taşınabilmesi nedeniyle yaprak nematodlarının mücadelesi zordur (Jagdale ve Grewal, 2006; El-Saadony ve ark., 2021). Bununla birlikte, yaprak nematodlarının mücadelesinde üstten sulama yerine damla sulama kullanılması ve enfekte bitkilerle temas eden alet ve ekipmanların, saksıların ve toprağın fırınlama veya buharlama yoluyla ısıl işleme tabi tutularak sanitasyonu önem arz etmektedir (Mitiku, 2018). Diğer uygulamalar arasında bulaşık bitkilere sıcak su uygulaması (Jagdale ve Grewal, 2004; Kohl, 2011; Mitiku, 2018); hümik asit kullanımı (Nagachandrabose ve Baidoo, 2021) ve bazı bitki türleri açısından dayanıklı çeşitlerin kullanımı (Kohl, 2011; Mitiku, 2018; El-Saadony ve ark., 2021) yer almaktadır.



Şekil 4. Yaprak nematodlarının krizantem yapraklarında oluşturdukları karakteristik büyük v şeklindeki lezyonlar (Horst, 2008)

3.3.Soğan-sak Nematodu (*Ditylenchus dipsaci*)

Polifag bir tür olan ve 450'den fazla bitki türünde zarar yapan *Ditylenchus dipsaci* kardelen (*Galanthus* spp.), süsen (*Iris* spp.), sümbül (*Hyacinth* spp.), sümbülcük (*Scilla* spp.), nergis (*Narcissus* spp.), soğan (*Allium* spp.), alev çiçği (*Phlox* spp.) dahil olmak üzere birçok süs bitkisinde zarar yapmaktadır (Agrios 2005; Slootweg, 1960). Soğan sak nematodunun genel belirtileri arasında yapraklarda ve gövdelerde şişme ve bükülme, gövde tabanlarında, soğanda, yumrularda ve rizomlarda nekroz veya çürüme yer alırken yoğun bulaşıklıklarda fide ölümü de meydana gelebilir. Lalede, toprak üstü kısımlar birleşebilen açık sarıdan beyaza lekeler veya şişlikler sergiler ve beyaz, düzensiz kenarlarla epidermiste çatlamalar meydana gelir. Lale çiçeklerinde özellikle karakteristik semptomlar arasında siğil büyümelerine dönüşen şişlikler yer alır ve genellikle gövde enfeksiyon bölgesinin üzerindeki taç yaprağının bir kısmı tamamen veya kısmen yeşil kalır. Etkilenen soğanlar depolama sırasında sık sık kurur ve ikincil olarak Penicillium ve akarlardan etkilenir (van Aartrijk ve ark., 2000). *D. dipsaci* ile enfekteli nergis bitkilerinde bodurlaşma, yaprak deformasyonları, renk değişimleri ve çiçeklenme oranında düşüş görülmektedir. Enfekteli soğanların iç dokularında ise çürüme ve kabuk altında nematod birikimi gözlemlenmiştir (Borazancı ve Çınarlı, 1996). *D. dipsaci*, glayöl bitkisinin soğanlarında ciddi ekonomik kayıplara neden olabilmektedir. Nematod enfeksiyonu bitkide deformasyonlara, yapraklarda sararma, kıvrılma, bodurluk gibi gelişim bozukluklarına ve çiçeklenmenin azalmasına yol açmaktadır. Enfekte soğanlarda çürüme ve dış yüzeyde doku yumuşaması görülebilir. Bu belirtiler çoğunlukla vejetatif dönemde ortaya çıkarken, ilerleyen enfeksiyonlar bitkinin ölmesine kadar varan sonuçlar doğurabilir (Tenente, 1996).

Ditylenchus dipsaci, soğanlarda, gövdelerde ve yapraklarda hareketli endoparazit olarak zarar yapmaktadır. Olumsuz çevre şartları altında dormant evresine girme yeteneğine sahip olan *D.*

dipsaci, yalnızca yoğun soğan çürümesi gibi elverişsiz koşullar sırasında toprağa girmektedir. Bitki dokusundan dışarı çıkan nematod kurumuş soğanların taban plakalarının etrafında nematod yumağı şeklinde grimsi beyaz, pamuksu kütleler halinde birikir ve bu kütleler sayesinde birkaç yıl boyunca uykuda kalabilirler. Bununla birlikte, *D. dipsaci*, bazıları sınırlı bir konukçu aralığına sahip olan 20'den fazla biyolojik ırka sahiptir (Anonymous, 2017). Nematod, enfekte üretim materyalinin yanı sıra su, rüzgar ve makinelerle taşınan kontamine toprak, sulama suyu ve rüzgar gibi faktörlerle yayılır (van Aartrijk ve ark., 2000). Mücadelesinde temiz üretim materyalinin kullanılması konukçusu olmayan bitkilerle münavebe yapılması, konukçusu olan yabancı otlarla mücadele edilmesi önem arz etmektedir. Sıcak su uygulamasında da başarılı sonuçlar elde edilmiştir (van Dam, 2013). Fumigasyon uygulamasından etkili sonuçlar elde edilirken aldicarb veya oxamyl gibi nematisitlerin çoklu tarla uygulaması, enfekte lale soğanlarının sayısını önemli ölçüde azaltmış, ancak yüksek derecede enfekte soğanlarda *D. dipsaci*'ye karşı tam etkili olmamıştır (Weststeijn ve De Rooy 1974; Windrich 1985).

3.4.Virüs Vektörü Nematodlar

Nematodlarla taşınan viruslar, nepoviruslar ve tobraviruslar olarak 2 farklı gruba ayrılırlar. Partikülleri çok düzlemli olan nepoviruslar, Cadman (1963) tarafından nematode transmission and POlyhedral particle shape'den isimlendirilmiştir. 1971 yılında da çubuk şeklinde partikülleri olan ve nematodlar tarafından taşınabilen tobra viruslar ise TOBacco RAttle virusun ilk harfleri alınarak oluşturulmuştur (Harrison et al. 1971). Pratikte bütün nematodlar, virusla bulaşık bitkilerde beslenirler ve virus parçalarını vücutlarına alırlar. Ancak 30'dan fazla familyaya bağlı yaklaşık 200 cinse ait 4100'den fazla bitki paraziti nematod türü bilinmesine karşın virüsleri taşıyan türler, bitkilerdeki parazit nematodların sayısının %1'inden fazlasını oluşturmaz. Virüs vektörü yaklaşık 44 tür bulunmakta olup bunlar, Dorylaimida takımının Longidoridae ve Trichodoridae familyalarına dahildir (Abdalreda ve Mohammed, 2022). Yapılan çalışmalar sonucunda nepovirusların sadece Longidoridae familyası tarafından, tobravirusların ise sadece Trichodoridae familyası tarafından taşındığı belirlenmiştir. Beslenmeleri sırasında vektörü oldukları virüsleri temiz bitkilere bulaşmasını sağlayan Longidorid ve Trichodorid nematodlarının her ikisi de, hem tek hem de çok yıllık bitkilerin köklerinde ektoparazittirler ve virus transferine ek olarak, üründe doğrudan zarara da neden olular (Weischer 1993).

Nepo virüsleri *Xiphinema* (kamalı nematodlar) ve *Longidorus* (iğne nematodları) cinslerinde yer alan bazı türler tarafından taşınmaktadırlar. *Xiphinema* ve *Longidorus* cinsleri 1,5-13 mm arasında değişen boyları ile en uzun bitki paraziti nematodları arasındadırlar ve beslenmeleri için kökün derinlerine girmelerini sağlayan uzun stiletleri vardır (Trudgill ve ark., 1991; Weischer, 1993). Konukçuları arasında çok yıllık ve odunsu bitkiler, sebzeler, meyveler ve süs bitkileri yer almaktadır (Weischer, 1993; Martelli ve Taylor, 1989). Sardunya, petunya ve lale gibi süs bitkileri için başlıca NEPO virüsleri domates halka lekesi virüsü (ToRSV), tütün halka lekesi virüsü (TRSV), Arabis mozaik virüsü (ArMV) ve domates siyah halka (TBRV) virüsüdür (Engelmann ve Hamacher, 2008). Çok sayıda NEPO virüsü olmasına rağmen, genel semptomlar arasında belirgin halka ve mozaik çizgili desenler, klorotik beneklenme, beneklenme, yaprak kıvrılması ve nekroz, bodur bitkiler ve genel bitki düşüşü yer alır (Şekil 5).



Şekil 5. Zambakta Arabis mosaic virüs enfeksiyonu sonucu oluşan mozaik ve nekrotik çizgiler ve noktalar (Chastagner ve ark., 2018)

TOBRA virüsleri ise 0,5-1,5 mm boyları ile bitki paraziti nematodlar arasında orta büyüklükte olan nematodlar gurubuna giren ve kıvrık bir stilete sahip kalın nematodlar olan *Trichodorus* ve *Paratrichodorus* türleri (küt kök nematodları) tarafından bulaştırılırlar (Abdalreda ve Mohammed, 2022). Kök ucundan ektoparazit olarak beslenerek kök uçlarının şişmesine ve güdükleşmesine neden olurlar (Taylor, 1972). Başlıca virüsler petunya, şakayık, lale ve zambak gibi bitkileri etkileyebilen Tobacco mosaic virus (TMV), Tobacco rattle virus (TRV), Pea early-browning virus (PEBV) ve Pepperringspot virus (PepRSV)'dür (Taylor, 1972; Handoo, 1998; Engelmann and Hamacher, 2008; Macfarlane, 2010;Khan, 2015). TOBRA virüslerinin genel belirtileri arasında yapraklarda klorotik ve nekrotik lekeler veya şeritler, mozaik, beneklenme, çiçek taç yapraklarında açık veya koyu renkli benekler, oval lezyonlar, çiçek malformasyonu ve bodur bitkiler yer alır (Engelmann ve Hamacher, 2008; Madhavan ve ark., 2021) (Şekil 6).



Şekil 6. Tobacco rattle virüsünün şakayık yapraklarında neden olduğu halka lekeleri (Garfinkel ve Chastagner, 2018)

Virüsün yayılmasını ve bulaşmasını önlemek için bu nematodların yönetimi, yalnızca virüssüz ekim malzemelerinin kullanılmasını, hijyenik önlemleri ve alet ve ekipmanların dezenfeksiyonunu, termoterapiyi, inokulumun yayılmasını önlemeye yardımcı olmak için virüsle enfekte olmuş bitkilerin yok edilmesini ve bitkilerin düzenli olarak analiz edilmesini içerir (Taylor, 1972; Engelmann and Hamacher, 2008; Adaskaveg ve Caprile, 2009; Madhavan et al., 2021). Yabancı ot kontrolü, nematodlar için alternatif konukçular olarak hizmet edebildikleri ve virüs rezervuarları olarak hareket edebildikleri için özellikle önemlidir.

Örneğin, karahindiba, *Taraxacum officinale* ve diğer geniş yapraklı yabani otlar virüsleri barındırabilir ve nematodlar bu bitkilerle beslenmeleri esnasında aldıkları virüsleri daha sonra aynı tarladaki süs bitkilerine bulaştırabilirler (Adaskaveg ve Caprile, 2009). Nematod vektörünü kontrol etmek için fumigantlar bir yönetim seçeneği olarak ekim öncesi kullanılabilir. Ayrıca hem nematoda hem de virüse dayanıklı çeşitlerin kullanılması hem etkili hem de çevre dostu mücadele yöntemleri arasındadır (Howland ve Quintanilla, 2023). Örneğin, lalelerde 'Cantata', 'Juan', 'MadameLefeber' ve 'Princeps' gibi TBV'ye dayanıklı birkaç çeşit bulunmaktadır (Madhavan ve ark., 2021).

3.5.Diğer Bitki Paraziti Nematodlar

Süs bitkilerinde zarar yapan birçok bitki paraziti nematod türü bulunmaktadır. Diğer önemli bitki paraziti nematodlardan biri konukçuları arasında nergis zambağı (Christie ve Birchfield, 1958; Nong ve Weber, 1965), eğrelti otları (Rhoades, 1968) ve kauçuk bitkileri gibi yapraklı bitkiler (Pinochet ve Duarte, 1986) dahil olmak üzere 400'den fazla bitki türünü barındıran ve hareketli endoparazit olan *Pratylenchus* spp. (kök lezyon nematodları) türleridir. Süs bitkilerinde lezyon nematodu beslenmesinin belirtileri arasında kök ve sürgünlerde bodurlaşma, klorotik yapraklar, yapraklarda renk değişikliği, solgunluk, kök şişmesi, kahverengi lezyonlar, tüm kök sistemlerinin tahrip olması ve ciddi verim kaybı yer almaktadır (Christie ve Birchfield, 1958; Rhoades, 1968; Mitiku, 2018). Belirtiler ayrıca bitki köklerinde nekrotik lezyonları da içerebilir ve bu durum hastalık komplekslerine neden olan bakteri ve fungusların ikincil enfeksiyonlara neden olabilir (Howland ve Quintanilla, 2023). Zambak (Lilium cv. Stargaze) bitkilerinde *Pratylenchus crenatus* ve *P. zeae* türleri tespit edilmiş, yumrular ve köklerde lezyonlara yol açtığı bildirilmiştir (Oliveira ve ark., 2012). Antoryum ve karabiberde ciddi seviyede zarar yapan ve 350'den fazla konukçusu bulunan *Radopholus similis* (oyuk nematodu) bir başka önemli hareketli endoparazit nematod türüdür (Haegeman ve ark., 2010; Khan, 2015). *Radopholus similis* kök ve gövdelerde beslenmesi sonucunda kök çürümesine, ciddi bitki bodurluğa ve kloroza neden olur ve bitki ölümlerine neden olabilir (Borgohain, 2016; Wang ve ark., 2016). Nematod, antoryum rizomlarında da damar demetlerini bozarak köklerde nekroz ve anatomik değişikliklere neden olabileceği gibi yeni tarlaların ekiminde kullanılan antoryum kamışlarında fark edilebilir herhangi bir belirti oluşturmayarak bu nematodun yayılmasına da neden olabilmektedir (Vovlas ve ark., 2003; Sipes ve Myers, 2018). *Rotylenchulus reniformis* (reniform nematod) bitki köklerine kısmen nüfuz eden yarı endoparazitik bir nematoddur. Bu nematodlar gündüz zambağı gibi bazı süs bitkilerinde hiçbir bitki belirtisi oluşturmazken pamuk gibi ürünler için yıkıcı parazitler olabilirler (Inserra ve ark., 1998; Koenning ve ark., 2004). *Paratylenchus* spp. (pin nematodu) gündüz zambağı gibi süs bitkilerinde yaygın olarak bulunmasına karşın bugüne kadar antoryumda zarar yapan *P. shenzhenensis* (Howland ve ark., 2022; Howland ve Quintanilla, 2023; Wang ve ark., 2016) dışında süs bitkilerinde bu nematod türü hakkında çok az araştırma yapılmıştır. *Paratylenchus* spp. enfeksiyonunun belirtileri arasında bodurluk, düşük kaliteli bitkiler ve verim azalması yer almaktadır (Howland ve Quintanilla, 2023).

4. BİTKİ PARAZİTİ NEMATODLARIN MÜCADELESİ

Süs bitkilerinde önemli derecede zarar yapan bitki paraziti nematodlar bunun sonucu olarak süs bitkileri endüstrisi açısından milyonlarca dolar kayıplara neden olmaktadırlar. Mevcut mücadele stratejilerinin çok etkili olmaması nedeniyle süs bitkilerinde bitki paraziti nematodların mücadelesi bazı zorluklar içermektedir. Bu durum özellikle etkinliği yüksek birçok nematisitin yasaklanması, belirti göstermeyen üretim materyalleri nedeniyle önemli türlerin hızla yayılması ve genel bilgi eksikliğinden kaynaklanmaktadır. Özellikle de gündüz zambağı ve iris gibi birkaç yıl boyunca sadece tarlada yetiştirilen süs bitkileri için, mevcut

yönetim stratejileri sıcak su uygulamaları ve dikim öncesi fümigasyondan oluşmaktadır. Sıcak su uygulamaları *D. dipsaci*, *A. fragariae* ve *R. similis* gibi endoparazit bitki paraziti nematodlara karşı kullanılabilmektedir ve dikim materyaline sıcak su uygulaması tohum, çiçek soğanı, yumru, rizom ve köklerin nematodlar açısından kontrolünde çok etkili olabilmektedir (Whitehead 1998). Genel olarak sıcak su uygulaması çıplak köklü bitkiler, yumrular gibi üretim materyallerinin büyük bir sıcak su tankına daldırılması ve ardından ikincil su tanklarında soğutulması şeklinde yapılmaktadır. Ancak sıcak su uygulaması endoparazitik nematodlara etkili olabilirken toprakta yaşayan ektoparazit nematodlara karşı kullanılamamaktadır. Ektoparazitik nematodlarla bulaşık olan toprağa ısıl işlem görmüş bitkilerin ekilmesi zararı engellemeyecektir. Ayrıca sıcak su uygulamasında süre ya da sıcaklık seviyesindeki hatalar bitki ölümlerine, canlılığın azalmasına neden olabileceği gibi nematodların canlılığını korumasıyla da sonuçlanabilir (Rhoades, 1964; Jagdale ve Grewal, 2004; Tsang ve ark., 2004; Howland ve ark., 2022). Bu nedenle sıcak su uygulamalarında, hedef materyali istenilen süre ve sıcaklıkta tutulabilmesini sağlayan tanklar ve ekipmanlar gerekmektedir (Sikora, 2005). Bitkileri sadece sıcak su yerine nematisitlere daldırmak alternatif bir yönetim stratejisidir. Kök-ur nematodlarına yönelik olarak gündüz zambağı fidelerinin dikimden önce fluopyram solüsyonuna daldırılması sonucunda kontrol ve Telone II fümigasyonuna kıyasla daha yüksek biyokütleye sahip bitkiler elde edilirken kök-ur nematodu zararının orta düzeyde kontrolü sağlanmıştır (Howland ve ark., 2022). Bununla birlikte, nematisitlerin çok yıllık bitkilerde ekim öncesi daldırma veya hasat sonrası uygulama olarak kullanımına yönelik olarak daha fazla çalışmaya ihtiyaç duyulmaktadır (Howland ve Quintanilla, 2023).

Bir diğer önemli mücadele stratejisi olan toprak fumigasyonu, fitotoksik olduğu için bitkiler topraktayken değil, yalnızca ekimden önce uygulanabilmektedir (Noling, 2008). Bu durum özellikle çok yıllık süs bitkilerinde nematodların yetersiz kontrolüyle sonuçlanmaktadır. Ayrıca fumigant nematisitlerin yüksek maliyet ve çevre riski taşıması nedeniyle bitkinin arazide olduğu dönemde de uygulanılabilen kontakt veya sistemik nematisitlerin kullanımı daha avantajlı durmaktadır (Zasada ve ark., 2010). Ancak Aldicarp, Carbofuran, Cadusafos, Ethoprophos gibi pekçok non-fumigant nematisitin kullanımı da yasaklanmıştır (Anonim 2020). Bununla beraber daha düşük çevresel etkiye sahip ve umut verici kontrol seviyelerine sahip fluensulfone, tioxazafen ve fluopyram gibi yeni nematisitlerin ruhsatlandırılması olumlu bir gelişmedir (Daughtrey ve Benson, 2005; Phani ve ark., 2021; Howland ve ark., 2022).

Dünya çapında yaklaşık yüz bin süs bitkisi türü ve bunların yabani akrabaları olduğu tahmin edilmesine karşın süs bitkilerinin bitki paraziti nematodlara konukçuluk durumlarının belirlenmesine yönelik çalışmalar son derece sınırlı kalmıştır (Howland ve Quintanilla, 2023; Long ve ark., 2018). Örneğin, 83.000'den fazla kayıtlı gündüz zambağı çeşidi olmasına karşın sadece birkaç çeşidin *M. Hapla*'ya konukçuluk durumu belirlenmiş durumdadır (Howland ve Quintanilla, 2023).

Birçok bitki türü açısından en önemli mücadele aracı nematodlara dayanıklı bitki kullanılmasıdır (Sikora ve ark., 2005). Yüksek etkinlik sağlaması, kullanımının kolaylığı, ekstra bir maliyet gerektirmemesi ve çevreye yan etkisinin bulunmaması dayanıklı çeşit kullanımının en önemli kazanımlarıdır. Bununla beraber birçok bitki türünde çoğu nematoda karşı dayanıklı çeşit bulunmamaktadır. Süs bitkilerinde de benzer bir durum söz konusudur.

Yapılan çalışmada üç farklı gerbera çeşidinde *M. İncognita* üreme oranının 1,9 ila 2,7 arasında değiştiği, 14 farklı karanfil çeşidinde ise üç çeşitte üreme görülmezken diğer çeşitlerde ise üreme oranının 0,8 ila 3,9 arasında değiştiği belirlenmiştir (Yarba, 2019). Bir diğer çalışmada ise dört farklı karanfil çeşidinin kök-ur nematodlarına dayanıklılık durumları belirlenmiş ve *M. İncognita, M. Javanica ve M. Arenaria* türlerine Turbo çeşidinin dayanıklı, Betsy ve Glaciar

çeşitlerinin hassas, Nirvana çeşidinin ise *M. İncognita*, *M. Javanica*'ya orta dayanıklı, *M. Arenaria*'ya ise tam dayanıklı olduğu ortaya konmuştur (Sert Çelik ve ark., 2022). Görüldüğü üzere yapılan çalışmalarda sonuçlar elde edilmesine rağmen süs bitkilerinde bitki paraziti nematodlara yönelik olarak yürütülen çalışmalar çok sınırlı düzeyde kalmış durumdadır. Önemli bir genetik çeşitliliğe sahip olan süs bitkilerinde dayanıklılık çalışmalarına ağırlık verilmesi son derece önemlidir.

Başarılı bir nematod mücadelesi yönetimi için hedef tür veya türlerimize, hedef alanımıza ve sahip olduğumuz teknik ve ekonomik imkanlara bağlı olarak kullanabileceğimiz kontrol metodolojilerinin hepsinin bir arada uygun şekilde kullanımını gerekmektedir. Bitki paraziti nematodların zararını azaltmaya yönelik olarak çevresel olarak sürdürülebilir yönetim stratejileri geliştirmenin en uygun yolu mücadelenin entegre zararlı yönetimi kapsamında sağlanmasıdır. Gelecekte süs bitkilerinde bitki paraziti nematodlardan kaynaklanan kayıpların azaltılmasına yönelik olarak yapılacak çalışmaların bu hedefler doğrultusunda oluşturulması etkili, çevreyle dost ve sürdürülebilir mücadele programlarının oluşturulması açısından büyük önem arz etmektedir.

5. SONUÇ

Dünya genelinde milyarlarca dolarlık ticaret hacmine sahip süs bitkileri sektörü, bitki paraziti nematodlar (BPN) nedeniyle ciddi tehdit altındadır. Kök-ur nematodları (*Meloidogyne* spp.), yaprak nematodları (*Aphelenchoides* spp.), soğan sak nematodu (*Ditylenchus dipsaci*) ve virüs vektörü nematodlar, süs bitkilerinde önemli ekonomik kayıplara yol açmaktadır. Bu zararlılar sadece doğrudan verim kaybına değil; kalite düşüşü, ihracatta karantina engelleri ve ikincil enfeksiyonlara da neden olmaktadır.

Mücadeledeki temel kısıtlar; zararlıların üretim materyaliyle hızla yayılması, belirtilerin diğer stres faktörleriyle karıştırılması ve etkili kimyasalların yasaklanmasıdır. Bu durum, sürdürülebilir yönetim yöntemlerinin geliştirilmesini zorunlu kılmaktadır.

Süs bitkilerinde nematod kaynaklı kayıpların minimize edilmesi için "Entegre Zararlı Yönetimi (IPM)" prensiplerinin benimsenmesi zorunludur. Gelecek araştırmaların; yerel nematod türlerinin belirlenmesi, dayanıklı çeşit ıslahı ve çevre dostu biyolojik mücadele ajanlarının etkinliğinin artırılması üzerine yoğunlaşması, sektörün sürdürülebilirliği açısından kritik öneme sahiptir.

6. KAYNAKLAR

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BENZEMEZ S690QL VE S355J2+N MALZEMELERİNİN G4Si1 DOLGU TELİ İLE ÇOK PASOLU KAYNAĞININ MEKANİK PERFORMANS DEĞERLENDİRMESİ

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ÖZET

Makine tasarımında malzeme seçimi yapıdan beklenen mekanik ve kimyasal özelliklere göre yapılır ancak bir malzeme her zaman istenen tüm özellikleri karşılamayabilir. Bu durumda farklı malzemelerin bir arada kullanılması iyi bir çözümdür ve aynı zamanda maliyeti düşürmeye önemli katkı sağlar. Ancak farklı malzemelerin bir arada kullanılmasında birleştirme sorunları ortaya çıkabilir. Özellikle endüstride yaygın bir üretim yöntemi olan kaynaklı imalat ile birleştirilmiş parçalarda malzemelerin mekanik veya kimyasal özelliğinde bir kayıp söz konusu olabilir. Bu sebeple farklı malzemelerin kaynaklı birleştirmelerinde kullanılan telin ve kaynak parametrelerinin kaynaklı bağlantının dayanımına etkisi incelenmelidir. Bu çalışmada farklı mekanik özelliklere sahip yüksek dayanımlı yapı çeliği S690QL ve normal dayanımlı yapı çeliği olan S355J2+N malzemelerinin kaynaklı birleştirilmesinde G4Si1 telinin çok pasolu uygulanması ile elde edilen kaynaklı bağlantının çekme mukavemeti, kaynak bölgesinin darbe dayanımı ve sertlik değerleri üzerinden bir performans değerlendirmesi yapılmıştır. 30 mm kalınlığındaki plakaların ilgili standartlara uygun olarak hazırlanmış test numuneleri ile yapılan deneylerde 535,8 MPa çekme dayanımı elde edilmiştir ve bağlantının S355J2+N malzeme tarafından koptuğu gözlemlenmiştir. Kaynak dikişinin çentikli darbe enerjisi 58,8 J olarak ölçülmüştür. Kaynak dikişinin merkezinde sertlik değeri ortalama 211 HV olup kaynak dikişinin yüzeylerine yakın bölgelerde alınan ölçümlerde sertlik değerlerinin 182-185 HV bandında olduğu görülmüştür. Kaynaklı bağlantının mekanik performansının normal dayanımlı yapı çeliği olan S355J2+N malzemeye yakın olduğu sonucuna varılmıştır.

Anahtar Kelimeler: GMAW, SG3, Çekme dayanımı, Kaynak parametreleri

MECHANICAL PERFORMANCE ASSESSMENT FOR MULTIPASS WELDING OF DISSIMILAR S690QL AND S355J2+N MATERIALS USING G4SI1 FILLER WIRE

ABSTRACT

In machine design, material selection is dictated by the required mechanical and chemical properties expected from the structure; however, a single material may not always meet all desired specifications. In such cases, the integration of dissimilar materials constitutes an effective solution and significantly contributes to cost reduction. Nevertheless, the concurrent use of different materials can lead to joining issues. Specifically, in components assembled using welded manufacturing, a common production method in industry, a potential loss in the mechanical or chemical properties of the materials may occur. For this reason, the effect of the filler wire and welding parameters utilized in the welding of dissimilar materials on the joint strength needs to be thoroughly investigated. In this study, a performance evaluation was conducted based on the tensile strength, weld zone impact toughness, and hardness of the welded joint implemented by the multi-pass application of G4Si1 filler wire when joining high-strength structural steel S690QL and normal-strength structural steel S355J2+N, which possess differing mechanical properties. The experiments, conducted using test specimens prepared in accordance with relevant standards from 30 mm thick plates, yielded a tensile strength of 535.8 MPa. It was observed that the joint fractured through the S355J2+N base material side. The notched impact energy of the weld bead was 58.8 J. The average hardness value at the center of the weld bead was 211 HV, while measurements taken in the regions near the weld bead surfaces indicated a hardness in the 182-185 HV range. It was concluded that the mechanical performance of the welded joint closely approaches that of the normal-strength structural steel S355J2+N.

Keywords: GMAW, SG3, Tensile strength, Welding parameters

1. INTRODUCTION

Material selection within machine design is governed by the requisite mechanical and chemical attributes demanded by the structure; however, it is frequently the case that a single material fails to satisfy all intended properties. In this context, the integration of dissimilar materials constitutes an optimal solution and provides a substantial advantage in terms of cost reduction. Nonetheless, the utilization of varied materials introduces inherent joining challenges. Specifically, components assembled via welding fabrication are susceptible to a resulting compromise in the materials' mechanical or chemical integrity.

S690QL steel is a High-Strength Low-Alloy (HSLA) steel that offers superior performance in terms of yield strength, weldability, and corrosion resistance compared to mild steel (Qiang et al., 2012). HSLA steels are favored in sectors such as the shipbuilding, marine engineering, bridge construction, mining, and the automotive industry (Vaikar et al., 2022; Ye et al., 2023). The combination of structural steels with dissimilar materials constitutes a favorable practice within the industry to lower costs. Studies have been conducted on the combined use of HSLA steels with various structural steels. Sorger et al. (2018) investigated the microstructure and fatigue properties of S690 and S355 steel plates joined by the Friction Stir Welding (FSW) method. Šmak et al. (2017) conducted a study on the Gas Metal Arc Welding (GMAW) of S355J0 steel and Weldox 700 (the trade name for the S700 steel product) using the standard Autrod 12.51 wire electrode. Astuti et al. (2023) evaluated the effects of the flame straightening process on the hardness of dissimilar S355J2+N and S690Q steel joints, which were welded using the GMAW method with a single V-groove. In their study, microstructural changes were investigated after the joints were subjected to the flame straightening treatment. Szusta et al. (2023) investigated the influence of both welding parameters and plate thickness on the strength of welded overlay joints utilizing S355 and Strenx 700 steels for agricultural machinery applications. Brätz et al. (2023) conducted a comprehensive study on the weldability and load-carrying capacity of multi-layer GMAW butt joints, focusing on the welding of S690, S700, and S960 high-strength structural (HSS) steels to S355 normal-strength structural steel. As part of the investigation, 10 mm and 20 mm thick plates made of S355 and S690 steels were examined to reveal the influence of the filler metal and heat input on the load-carrying capacity of the welded joints. In this study, the mechanical performance of multi-pass welded S690QL and S355J2+N materials was evaluated by examining the tensile strength, Charpy V-Notch (CVN) impact toughness, and hardness of the welded joint. This welding was performed using the GMAW method, a technique widely employed in industry, with G4Si1 filler wire. A multi-pass welding procedure was implemented for the joining of the 30 mm thick plates.

2. MATERIALS AND METHODS

2.1. Materials used and welding process

This study investigated the performance of G4Si1 (conforming to AWS A5.18/ER70S-6 and EN ISO 14341-A/G 46 3 M G4Si1 specifications) filler material when utilized in the GMAW welding of S355J2+N and S690QL steels. The chemical composition and mechanical properties of the base materials and the G4Si1 filler wire are detailed in Tables 2.1 and 2.2. The certified chemical composition data for the filler material were obtained from the manufacturer.

Table 2.1. Chemical composition (wt.%) of materials and filler wire

%	Fe	C	Si	Mn	P	S	Ni	Cr	V	Mo	Al	Cu
S690QL	Base	0.013	0.030	1.18	0.009	0.001	0.10	0.25	0.030	0.146	0.54	0.01
S355J2+N	Base	0.070	0.019	1.39	0.021	0.024	0.14	0.12	0.042	0.021	0.020	0.46
G4Si1	Base	0.08	1.00	1.70								

Table 2.2. Mechanical properties of base plates and filler wire

	S690QL	S355J2+N	G4Si1
Yield Strength, MPa	779	403	470
Tensile Strength, MPa	823	479	570
Toughness, J	235 (-40°C)	60 (20°C)	60 (-30°C)
Elongation, %	18	25	25

Plates measuring 200x350mm with a 30 mm thickness were prepared by grinding to form a 60° double-bevel groove for welding. The GMAW process was carried out manually in the flat (PA) position using reverse polarity (DC+). Shielding gas protection was provided by a mixture of 18% CO_2 and 82% Ar, maintained at a flow rate of 12 dm^3/min. A 1.2 mm diameter filler wire was employed. Arc stability was maintained throughout the process, resulting in a weld seam free of discontinuity. The interpass temperature was limited to 250 °C. Specific welding parameters for each pass are shown in Table 2.3.

Table 2.3. Welding parameters of GMAW process

Run	Current (A)	Voltage (V)	WS (mm/min)
Root pass	140-150	16-18	185
Hot passes	235-260	25-27	245-293
Fill passes	240-280	26-27	275-301
Cover pass	240-250	24-26	284

WS: Welding speed

2.2. Mechanical tests

Samples extracted from the welded plates underwent comprehensive mechanical testing, including tensile, Charpy impact, and Vickers hardness testing, with all relevant dimensions and measurement points (HMPs) shown in Fig. 2.1. Three tensile tests were performed according to the ISO 4136 standard (ISO, 2022a). For impact toughness evaluation, nine Charpy V-Notch samples were prepared (three each from the weld metal, the S355J2+N-HAZ, and the S690QL-HAZ) and according to ISO 9016 standard (ISO, 2022b). The Vickers hardness profile (HV10) was established by taking three repetitions at the S355J2+N base, its HAZ, the weld zone (WZ), the S690QL-HAZ, and the S690QL base, in line with ISO 9015 (ISO, 2016).

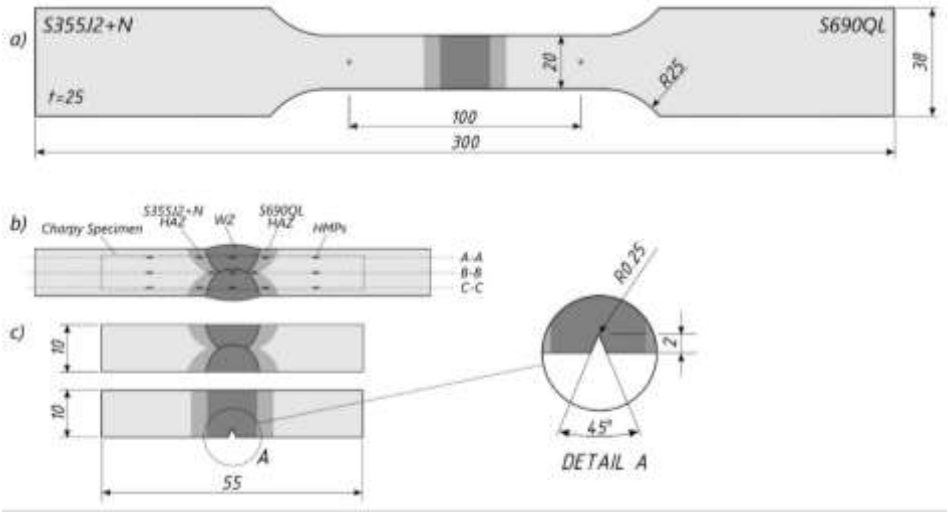

Fig. 2.1. Dimensions of specimens and Hardness measurement points. (a) tensile test specimen, (b) hardness specimen and (c) Charpy test specimen

3. RESULTS AND DISCUSSION

Fig. 3.1 provides a macrograph revealing the structure of the weldment cross-section. The image shows the layered application of the welding passes, defining both the weld zone (WZ) and the heat-affected zones (HAZs) surrounding the fusion line. The overall welding quality was satisfactory, exhibiting no discontinuities.

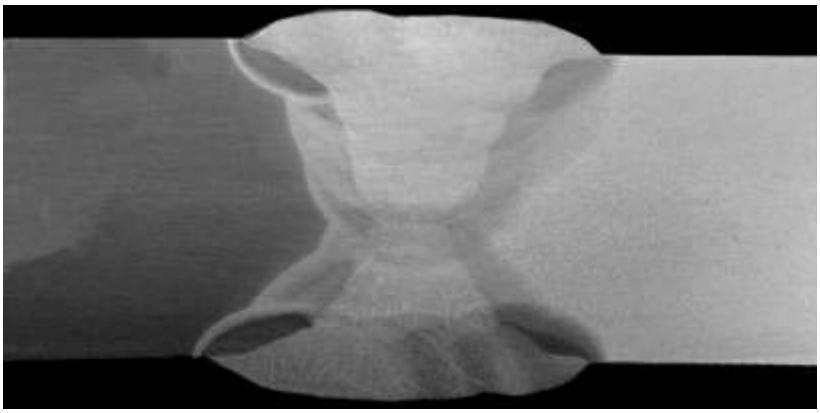

Fig. 3.1. Macrograph of welded specimen

The CVN results of the specimens were shown in Fig. 3.2. Significant differences were observed in the impact toughness values of the base materials, which were also reflected by a marked contrast in the characteristics of their respective HAZs. Specifically, CVN tests conducted on specimens extracted from the S690QL-HAZ exhibited an average absorbed energy of 280 J. In contrast, the value recorded for the S355J2+N side was considerably lower, measuring 54.4 J. The energy absorption capability of the weld metal itself closely resembled that of the S355J2+N base material, with an average measured value of 58.8 J. These obtained values surpass the minimum requirement of 27 J specified for the S355J2 steel grade at -20 °C according to the EN 10025-2 (EN 10025-2, 2004) standard.

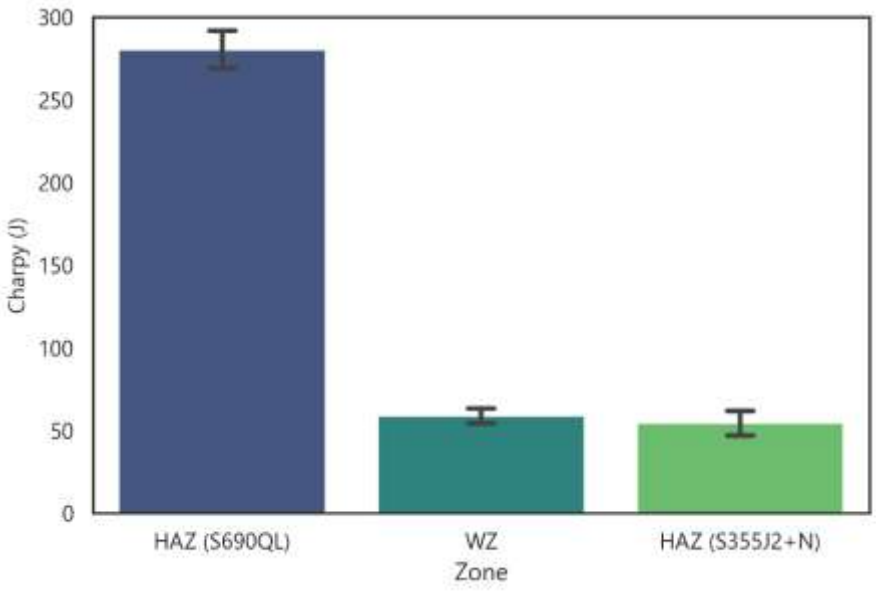

Fig. 3.2. CVN test results

Fig. 3.3 presents the hardness measurement values obtained from different regions of the welded joint. These regions are indicated in the figure as front side A-A, center B-B, and bottom side C-C. The S690QL base metal exhibited the highest hardness value, averaging 284 HV. In contrast, the hardness of the S355J2+N base metal averaged 168 HV. As shown in the figure, the hardness across the welded joint decreased smoothly from the high-strength steel side toward the normal-strength structural steel side. Hardness measurements taken from the front and bottom sides of the specimen showed a similar profile. Measurements taken from the center (B-B) indicated that the hardness in the center regions of the S690QL-HAZ was lower compared to the surface, while the hardness in the weld metal and the S355J2+N-HAZ was higher compared to the surface. This demonstrates the effect of multi-pass welding on the hardness profile.

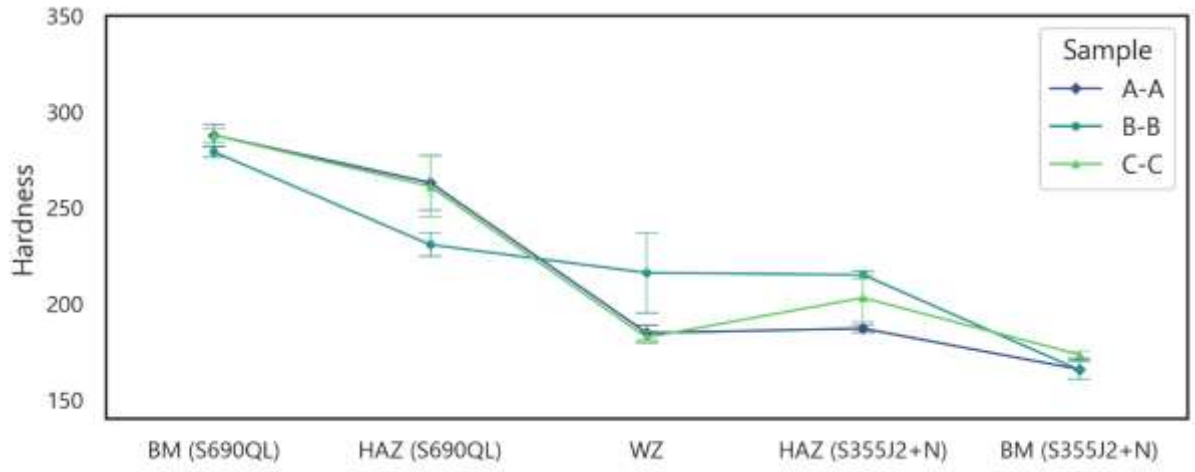

Fig. 3.3. Hardness of welded specimens (A-A: Front side, B-B: Center, C-C: Bottom side)

Table 3.1 shows the results of the tensile tests. Utilizing the selected wire and welding parameters, the welded joint achieved an average tensile strength of 535.8 MPa. All three test specimens, which exhibited an elongation of approximately 13-14%, fractured in the S355J2+N

base metal region. The resulting tensile strength of the welded joint is higher than that of the S355J2+N base material itself.

Table 3.1. Results of tensile tests

Sample	Rp0.2 (MPa)	Rm (MPa)	Elongation (%)	LoF
T1	382.9	535.4	13.6	Base (S355J2+N)
T2	376.9	536.0	13.9	Base (S355J2+N)
T3	377.5	535.9	13.6	Base (S355J2+N)
Avg.	379.1	535.8	13.7	

Rp0.2: Yield strength, Rm: Tensile strength, LoF: Location of fraction

4. CONCLUSION

The mechanical properties of GMAW-welded S690QL and S355J2+N materials using G4Si1 filler wire were investigated in this study. The main outcomes could be drawn as follows:

- The tensile strength of the welded joint was measured at an average of 535.8 MPa, a value that exceeds the strength of the S355J2+N, which has the lowest strength between the two joined materials.
- The impact toughness values obtained in the weld metal and the S355J2+N-HAZ were 58.8 J and 54.4 J, respectively, both of which are higher than the expected minimum value for the S355J2+N.
- As a consequence of the multi-pass welding process, the hardness value in the S690QL-HAZ at the center of the weld cross-section was lower compared to the surface. Conversely, higher hardness values than those observed on the surface were obtained in the weld metal and the S355J2+N-HAZ regions.

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BİR ALTIN MADENİ SİYANÜRLÜ ATIKLARININ ÇEVRESEL YÖNETİMİ VE SİYANÜR GİDERİMİ

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ÖZET

Altın madenciliğinde siyanür kullanımı, cevherden metal kazanımında sağladığı yüksek verimlilik nedeniyle dünya genelinde yaygın olarak tercih edilmekte; ancak siyanürün toksik özellikleri nedeniyle çevresel sürdürülebilirlik bağlamında sürekli tartışılmaktadır. Bu nedenle siyanürlü proses atıklarının etkin bir şekilde yönetilmesi, çevresel risklerin azaltılması ve yasal gerekliliklere uyum açısından kritik öneme sahiptir. Bu çalışmada, bir altın madeni sülfür tesisinde oluşan siyanürlü proses atıklarının detoksifikasyon, nötralizasyon ve depolama süreçleri bütünsel olarak değerlendirilmiştir. Özellikle zayıf asit ayrılabilir siyanür (WAD_CN) ve serbest siyanür (Free_CN) fraksiyonlarının arıtım sürecindeki değişimleri incelenmiş; ayrıca pH kontrolü ve bakır (Cu) konsantrasyonlarındaki dalgalanmalar da çevresel performans göstergeleri kapsamında analiz edilmiştir. Proses çıkışında Free_CN^- 15,30 ppm düzeyindeyken detoksifikasyon sonrasında <2,00 ppm'e kadar düşmüş, WAD_CN konsantrasyonu ise 182,30 ppm'den <2,00 ppm seviyesine gerilemiştir. Bu kayda değer azalma, kullanılan detoksifikasyon kimyasallarının ve proses optimizasyonunun etkinliğini ortaya koymaktadır. Arıtma süreci boyunca pH değeri kontrol altında tutulmuş, atık depolama tesisi (TSF) çıkışında pH 9,73'ten 8,19'a doğru düzenli bir düşüş elde edilmiştir. TSF çevresindeki

yeraltı suyu izleme kuyularında siyanür tespit edilmemesi ise taşınım ve sızıntı riskinin başarılı şekilde minimize edildiğini göstermektedir. Sonuçlar, incelenen altın madeninde siyanür yönetim zincirinin hem arıtım verimliliği hem de çevresel güvenlik açısından etkili şekilde işlediğini ve sürdürülebilir maden atık yönetimi açısından iyi bir uygulama örneği sunduğunu ortaya koymaktadır.

Anahtar Kelimeler: Altın madenciliği, Siyanür yönetimi, Zayıf asit ayrılabilir siyanür, Serbest siyanür, Çevresel performans.

ENVIRONMENTAL MANAGEMENT AND CYANIDE REMOVAL OF GOLD MINE CYANIDE-BEARING WASTES

ABSTRACT

The use of cyanide in gold mining remains one of the most debated issues in terms of environmental sustainability, despite its proven efficiency in metal recovery. Effective management of cyanide-bearing process residues is therefore essential to minimize ecological risks and ensure compliance with environmental regulations. In this study, the environmental management performance of cyanide-contaminated process effluents generated in a gold mine sulfide processing plant was comprehensively evaluated. Particular emphasis was placed on the behavior of weak acid dissociable cyanide (WAD_CN) and free cyanide (Free_CN) during detoxification and neutralization, as well as on the variations in pH and copper (Cu) concentrations as indicators of treatment efficiency. At the process outlet, Free_CN^- was measured at 15.30 ppm and was reduced to <2.00 ppm after detoxification. Similarly, WAD_CN, initially 182.30 ppm, decreased to <2.00 ppm following treatment. These substantial reductions demonstrate the effectiveness of the applied detoxification reagents and operational controls. Throughout the treatment chain, pH levels were carefully regulated, with a controlled decrease from 9.73 to 8.19 at the tailings storage facility (TSF) discharge point. Monitoring results from groundwater wells surrounding the TSF revealed no detectable cyanide, indicating that migration and leaching risks were successfully mitigated. Overall, the findings indicate that the cyanide management practices implemented at the investigated gold mine operate with high efficiency in terms of both process safety and environmental protection. The study provides a strong example of effective cyanide detoxification and environmentally responsible tailings management within modern gold mining operations.

Keywords: Gold mining, Cyanide management, Weak acid dissociable cyanide, Free cyanide, Environmental performance.

1. GİRİŞ

Altın madenciliğinde siyanür liçi yöntemi, düşük tenörlü cevherlerden ekonomik olarak altın kazanımını sağlayan en yaygın yöntemdir (Adams, 2016). Ancak siyanür; toksisitesi, taşkınlar sonrası su kaynaklarına karışma riski ve ekotoksik etkileri nedeniyle çevresel açıdan en tartışmalı reaktiflerden biri olarak değerlendirilmektedir (Hilson ve Monhemius, 2006; Kohio vd., 2025). Siyanür yönetimindeki yetersizlikler sonucu ortaya çıkan kazalar - örneğin 2000 Baia Mare (Romanya) taşkını ya da 2015 Bento Rodrigues (Brezilya) felaketi - çevresel madencilik literatüründe sıkça anılmakta ve risk farkındalığını artırmaktadır (Rico vd., 2008; Azam ve Li, 2010; Kemp vd., 2021). Bu olaylar, TSF (Tailings Storage Facility - Atık Depolama Tesisi) güvenliğinin ve proses atıklarının etkin arıtımının hem bilimsel hem de toplumsal düzeyde daha dikkatle değerlendirilmesine neden olmuştur.

Son yıllarda sürdürülebilir madencilik yaklaşımı, yalnızca metal kazanım süreçlerini değil, aynı zamanda atık yönetimi, çevresel izleme ve risk azaltma stratejilerini de içeren daha geniş bir çerçeveye dönüşmüştür (Hudson-Edwards vd., 2011). Bu kapsamda Sorumlu Yatırım İlkeleri (PRI), Uluslararası Madencilik ve Metaller Konseyi (ICMM) ve Birleşmiş Milletler Çevre Programı (UNEP) tarafından Küresel Atık Barajı İncelemesi (Global Tailings Review - GTR) başlatılmıştır. GTR'nin temel görevi, mevcut endüstriyel uygulamaları değerlendirmek, geçmiş baraj kazalarından edinilen dersleri analiz etmek ve bu doğrultuda Küresel Atık Yönetimi Standardı'nı (GTR Standardı) geliştirmektir. Güvenli atık tesisi yönetimine yeni bir ölçüt getirmesi hedeflenen standart, Kasım 2019'da taslak olarak yayımlanmış ve nihai sürümü Ağustos 2020'de kamuoyuyla paylaşılmıştır (Kemp vd., 2021). Brumadinho, Mariana ve Mount Polley gibi büyük ölçekli felaketler sonrasında maden atıkları yönetiminde siyanür bileşiklerinin izlenmesi küresel standartların merkezine yerleşmiş; GISTM (Global Industry Standard on Tailings Management) ile "sıfır zarar" ilkesi uluslararası düzeyde benimsenmiştir.

Altın madenciliğinde zayıf asit ayrılabilir siyanür (WAD_CN) ve serbest siyanür (Free CN^-) giderimi, hem küresel hem de Türkiye özelinde çevresel yönetimin en kritik unsurlarından biri olarak kabul edilmektedir. Free CN^- akut toksisite potansiyeli nedeniyle ekosistemler için doğrudan tehdit oluştururken; WAD_CN, bakır, çinko ve nikel gibi zayıf komplekslerden zaman içinde siyanür salabilmesi nedeniyle orta ve uzun vadeli çevresel risklere yol açabilmektedir. Kuyucak ve Akcil (2013), altın madenciliği kaynaklı atık akımlarında özellikle WAD_CN ve Free CN^- türlerinin düzenleyici limitlerin belirleyicisi olduğunu; bu bileşiklerin doğal bozunmaya dirençli olması ve metal kompleksleşmesi yoluyla çevresel taşınıma açık bulunması nedeniyle özel önem taşıdığını belirtmektedir.

Türkiye'de altın madenciliği faaliyetleri, SKKY (Su Kirliliği Kontrolü Yönetmeliği) ve AB uyum mevzuatı çerçevesinde WAD_CN için <1 mg/L, Free CN^- için ise daha düşük limitleri sağlamakla yükümlüdür. Ülkede yeraltı suyu güvenliği, sızıntı kontrolü ve atık barajı bütünlüğüne ilişkin tartışmalarda siyanür yönetimi toplumsal kabulün şekillenmesinde belirleyici bir faktör haline gelmiştir. Ayrıca 6331 sayılı İSG Kanunu ve ÇED (Çevrese Etki Değerlendirmesi) mevzuatı kapsamında, siyanürlü proses sularının detoksifikasyon ve nötralizasyon aşamalarından geçirilmesi zorunlu olup işletmelerin WAD_CN ve Free CN^- giderim performansını sahaya özgü verilerle raporlaması gerekmektedir.

Bu çalışmada, Türkiye'deki bir altın madeninde uygulanan siyanür yönetim zincirinin performansı saha ölçümlerine dayanarak değerlendirilmekte, literatürde yer alan benzer uygulamalarla karşılaştırılmakta ve elde edilen bulgular sürdürülebilir madencilik bağlamında tartışılmaktadır.

2. MALZEME VE YÖNTEM

2.1. Çalışma Sahası

Bu çalışma, Türkiye'de faaliyet gösteren büyük ölçekli bir altın madeni sülfür tesisinde yürütülmüş olup, bölge ülkenin en yüksek altın üretim merkezlerinden biri olarak bilinmektedir. Cevherin sülfürlü yapısı nedeniyle işletmede altın kazanımı siyanür liçi ile gerçekleştirilmektedir ve bu süreç sonrasında WAD_CN ve Free CN^- bakımından zengin siyanürlü proses atıkları oluşmaktadır. Atıkların depolanmasında geleneksel TSF sistemi kullanılmakta; tabanda geçirimsiz jeosentetik membranlar ve kompakte kil tabakalarından oluşan çok katmanlı bir sızdırmazlık altyapısı bulunmaktadır. Bu tasarım, ICMM (2020) ve Avrupa Birliği madencilik direktiflerinde belirtilen modern güvenlik standartlarıyla uyumludur.

İşletmede siyanürlü proses sularının çevresel etkilerini azaltmak amacıyla üç aşamalı bir siyanür yönetim zinciri uygulanmaktadır. İlk aşama olan detoksifikasyon, SO_2/Hava Prosesi veya hidrojen peroksit gibi oksidanlarla siyanürün daha az toksik siyanat (CNO^-) formuna dönüştürülmesini sağlamakta ve böylece WAD_CN ile Free CN^- konsantrasyonlarında belirgin düşüş yaratmaktadır. Bunu izleyen nötralizasyon aşamasında, pH kontrollü olarak 9,7 seviyesinden yaklaşık 8,2'ye düşürülmekte ve böylece HCN volatilizasyonu (buharlaşması) önlenmektedir. Son aşama olan TSF depolama sürecinde, çok katmanlı sızdırmazlık sistemi sayesinde arıtılmış proses atıkları güvenli biçimde depolanmakta; düzenli piezometre ölçümleriyle olası sızıntılar izlenmektedir.

Bu bütüncül sistem, "kaynakta azaltım → proses içi kontrol → nihai depolama güvenliği" yaklaşımıyla sürdürülebilir madencilik ilkelerine uygun bir model sunmakta ve siyanür yönetiminin hem çevresel hem de operasyonel açıdan etkin biçimde yürütülmesine olanak sağlamaktadır.

2.2. Örnekleme Noktaları ve İzlenen Parametreler

Bu çalışmada toplanan numuneler steril cam şişelere alınarak soğuk zincir koşullarında laboratuvara taşınmış ve analizler uluslararası kabul görmüş "Standard Methods" protokollerine göre gerçekleştirilmiştir (APHA, 2017). WAD_CN ve Free CN^- analizleri bu standartlara uygun olarak yapılmış, pH ölçümleri saha koşullarında kalibre edilmiş taşınabilir pH metre ile belirlenmiştir. Ayrıca bakır (Cu) konsantrasyonları, yüksek duyarlılığı ve düşük tespit sınırı nedeniyle çevresel madencilik araştırmalarında yaygın kullanılan ICP-OES (Inductively Coupled Plasma - Optical Emission Spectrometry) yöntemi ile ölçülmüştür.

Örnekleme dört kritik noktadan yapılmıştır. İlk nokta olan Proses Çıkışı, altın liçi işlemi sonrasında siyanürlü atık suyun en yüksek konsantrasyonlara sahip olduğu bölgeyi temsil etmektedir. İkinci nokta, siyanürün oksidatif kimyasal arıtımdan geçirildiği Detoks Çıkışı olup, burada siyanürün büyük bölümü daha az toksik türlere dönüşmektedir. Üçüncü örnekleme noktası olan TSF Çıkışı, atık depolama tesisine giriş sonrası bekletilen suyun kontrol noktasıdır ve depolama sisteminin çevresel güvenilirliğine ilişkin önemli veriler sunmaktadır. Dördüncü nokta ise Yeraltı Suyu İzleme Kuyularıdır; TSF çevresinde bulunan piezometrelerden alınan bu numuneler, olası sızıntıların yeraltı suyu kalitesine etkisini değerlendirmek amacıyla kullanılmıştır. Bu yaklaşım ile hem proses zinciri hem de çevresel alıcı ortam bütüncül bir şekilde incelenmiştir.

Çalışmada dört temel parametre izlenmiştir. WAD_CN, metallere komplekslenmiş siyanür fraksiyonunu temsil etmekte olup ekotoksik etkiler açısından en kritik bileşenlerden biridir. Free CN^-, HCN ve CN^- iyonlarını içeren ve akut toksisiteyi belirlemede kullanılan serbest siyanür formudur. pH, siyanürün uçucu HCN formuna dönüşüm riskinin yönetilmesinde temel bir parametre olup uluslararası standartlarda 9 - 10 aralığının korunması önerilmektedir (Freitas

ve Horta, 2023). Cu (bakır) ise siyanürle kompleks oluşturan başlıca metallerdendir ve hem proses kararlılığı hem de su kalitesi açısından çalışmada düzenli olarak izlenmiştir. Parametre seçimi WHO (2022) içme suyu standartları ve ICMM çevresel gereklilikleriyle uyumlu yapıdadır.

3. BULGULAR

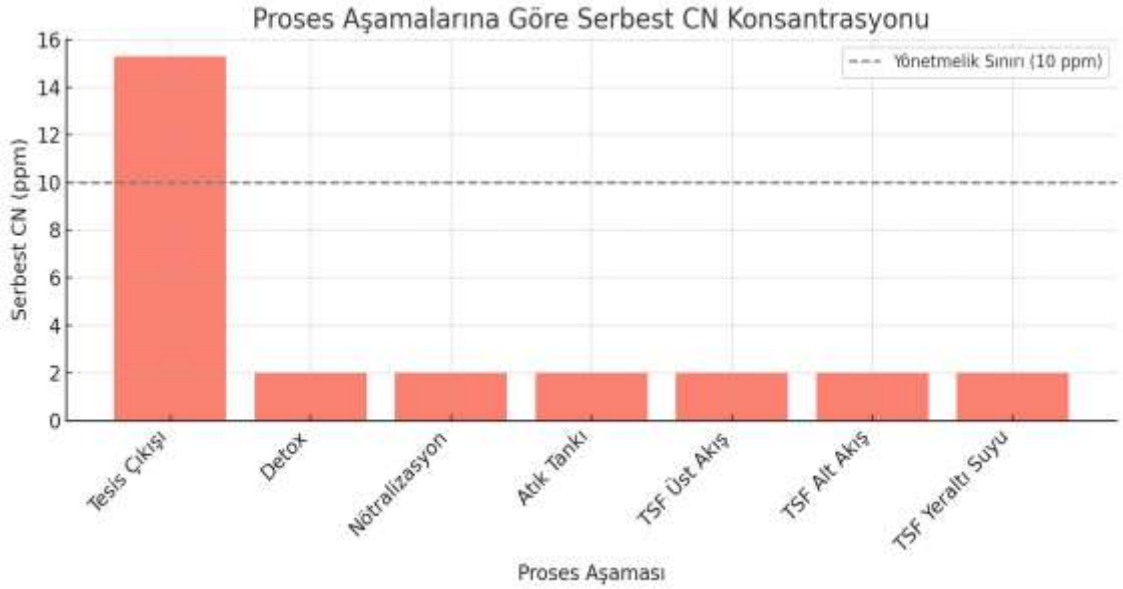
3.1. Siyanür Konsantrasyonlarının Azalması ve pH değişimleri

WAD_CN ve Free CN^- konsantrasyonlarının proses adımlarına göre değişimi Tablo 1'de verilmiştir.

Tablo 1. Kritik parametrelerin proses adımlarına göre değişimi.

Parametre	Proses Çıkışı	Detoks Çıkışı	TSF Çıkışı
Free CN^- (ppm)	15,30	<2,00	<2,00
WAD_CN (ppm)	182,30	<2,00	<2,00
pH	9,73	–	8,19

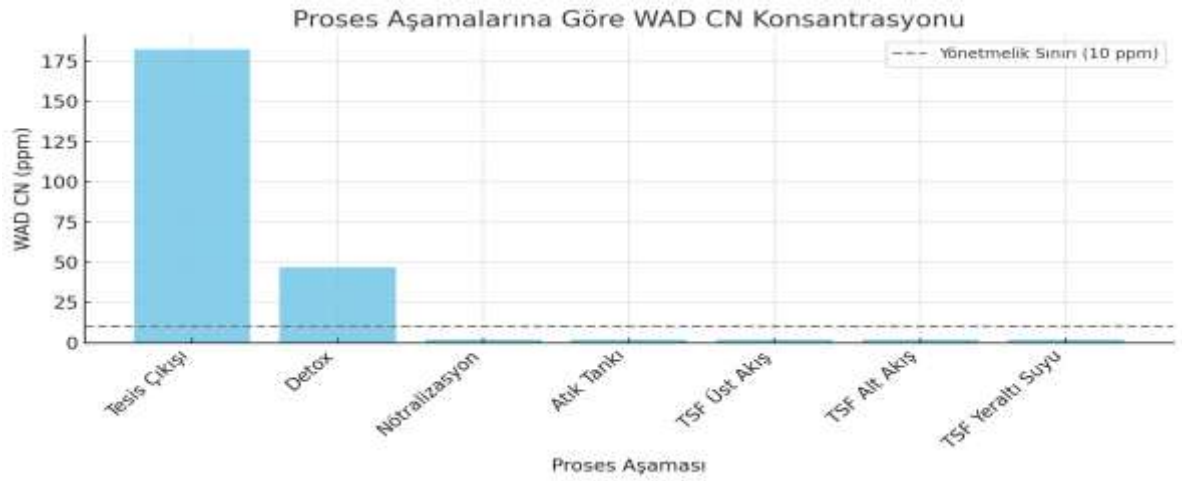
Free CN^- konsantrasyonu, detoksifikasyon aşamasında hızlı bir düşüş göstermiş ve TSF çıkışında <2 ppm seviyesinde sabitlenmiştir (Şekil 2).



Şekil 2. Free CN^- konsantrasyonlarının proses adımlarına göre değişimi.

Şekil 2'de Free CN^- değerinin detoksifikasyon sonrasında belirgin şekilde azaldığı ve TSF çıkışında uluslararası sınır değerlerin altında stabil kaldığı görülmektedir. Benzer şekilde WAD_CN değerleri, proses çıkışındaki 182,30 ppm seviyesinden detoks sonrası dramatik biçimde azalarak TSF çıkışında <2 ppm düzeyine gerilemiştir (Şekil 3).

Şekil 3, WAD_CN konsantrasyonlarının proses boyunca iki log mertebesine yakın bir azalma gösterdiğini ve TSF çıkışında çevresel standartlarla uyumlu seviyelere indiğini ortaya koymaktadır. Bu sonuçlar, detoksifikasyon ve nötralizasyon adımlarının siyanürlü proses atıkları üzerinde yüksek etkinlik sağladığını göstermektedir.

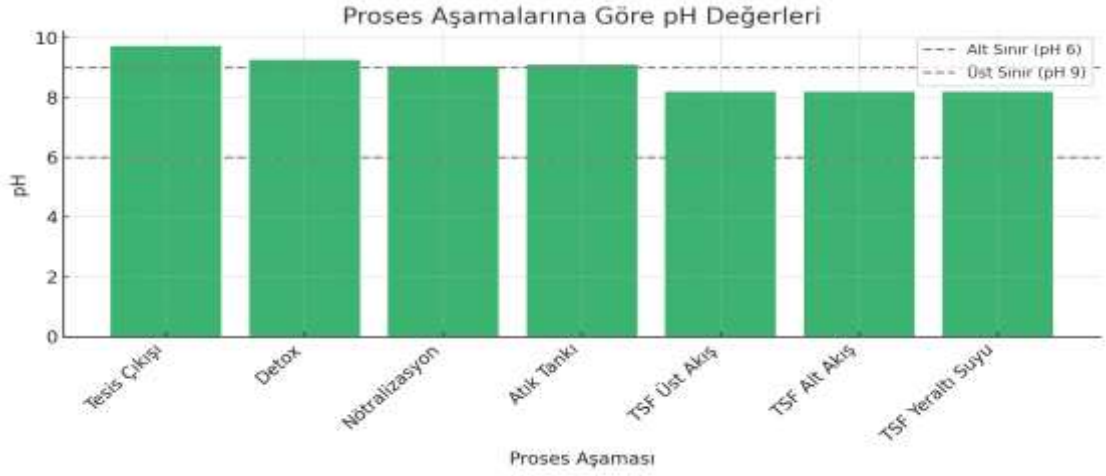


Şekil 3. WAD_CN konsantrasyonlarının proses adımlarına göre değişimi.

Altın Madeni'nde yapılan analizler, siyanür yönetim zincirinin (detoksifikasyon → nötralizasyon → TSF) etkinliğini açıkça kanıtlamaktadır. Saha bulguları, altın madenciliğinde çevresel güvenliğin yalnızca arıtma verimliliğine değil, aynı zamanda sürekli izleme ve kontrol mekanizmalarına bağlı olduğunu göstermektedir (Hudson-Edwards vd., 2011).

Çalışma sahasından elde edilen siyanür giderim oranları, Kanada'daki Musselwhite Madeni ve Avustralya'daki Fosterville Madeni gibi modern tesislerde rapor edilen sonuçlarla uyumludur. Bu tesislerde de WAD_CN konsantrasyonları <2 ppm düzeyine indirilmektedir (Adams, 2016; Vaca-Escobar vd., 2024). Avrupa Birliği'nin 2020 direktifleri, TSF çıkışında WAD_CN değerinin 10 ppm altında tutulmasını önermektedir. Sahada ölçülen değerlerin bu sınırın oldukça altında kalması, işletmenin çevresel standartlara uyum sağladığını göstermektedir.

pH değerleri proses çıkışında 9,73, TSF çıkışında ise 8,19 olarak ölçülmüştür (Şekil 4). Bu değerler, uluslararası literatürde önerilen 8-10 aralığı (Mudder ve Botz, 2004; ICMM, 2020) ile uyumludur. Kontrollü pH yönetimi, hem siyanürün çözeltide kalmasını sağlamış hem de HCN gazı volatilizasyonu riskini azaltmıştır.



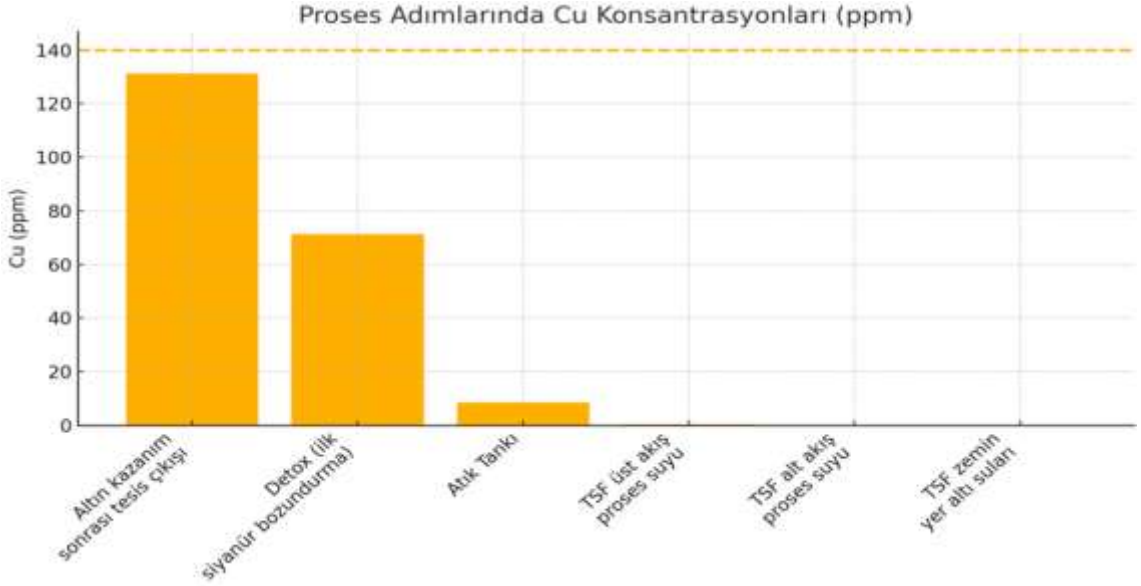
Şekil 4. Proses adımlarına göre pH değişimi

Siyanürlü proses atıklarında pH yönetimi kritik öneme sahiptir. pH 9-10 aralığında tutulduğunda HCN gazı oluşumu minimuma indirilmektedir (Lottermoser, 2010). Madende pH'ın 9,73'ten 8,19'a kontrollü düşüşü, siyanürlü suların çevresel salım riski olmadan TSF'ye

verilmesini sağlamıştır. Bu uygulama, ICMM (2020) tarafından önerilen "pH bariyeri" yaklaşımıyla uyumludur.

3.2. Bakır (Cu) Konsantrasyon Profili

Proses adımlarına göre bakır konsantrasyonlarının değişimi Şekil 5'te verilmiştir. Bulgular, Cu'nun proses boyunca dalgalanma gösterdiğini ancak TSF çıkışında çevresel limitlerin altında kaldığını ortaya koymuştur.



Şekil 5. Cu konsantrasyonlarının proses adımlarına göre değişimi.

TSF çevresindeki izleme kuyularından alınan yeraltı suyu numunelerinde siyanür, tespit sınırının altında bulunmuştur. Bu bulgu, TSF tabanında uygulanan jeosentetik sızdırmazlık sistemlerinin ve düzenli izleme programlarının etkili olduğunu göstermektedir.

Siyanürle kompleks oluşturabilen metallerden özellikle Cu, proses verimliliğini ve çevresel riskleri doğrudan etkilemektedir. Çalışma sahasında Cu konsantrasyonlarının TSF çıkışında düşük düzeyde kalması, detoksifikasyon sürecinde metal-siyanür komplekslerinin etkili şekilde parçalandığını göstermektedir. Benzer şekilde Yunanistan'daki Skouries Projesi için rapor edilen bulgular da detoksifikasyon sonrası Cu'nun tespit sınırının altında kaldığını ortaya koymuştur (Alexander vd., 2018; Ilyas ve Lee, 2018).

TSF çevresindeki piezometre kuyularında siyanür tespit edilmemiştir. Bu sonuç, TSF tabanındaki çok katmanlı jeosentetik sistemlerin başarılı bir şekilde işlev gördüğünü göstermektedir. Literatürde, sızdırmazlık sistemlerinin zayıf olduğu barajlarda (örneğin Baia Mare kazası, 2000) siyanürün hızla yeraltı sularına taşındığı bildirilmiştir (Rico vd., 2008). Çalışma sahasında bu riskin ortadan kaldırılması, baraj tasarımının uluslararası standartlara uygun olduğunun göstergesidir.

4. SONUÇLAR

Proses çıkışında yüksek düzeyde ölçülen WAD_CN (182,30 ppm) ve Free CN^- (15,30 ppm) konsantrasyonları, uygulanan detoksifikasyon işlemi sonrasında <2,00 ppm seviyesine düşürülmüştür. Bu değerler, Avrupa Birliği Direktifleri ve ICMM tarafından belirlenen uluslararası standartların öngördüğü limitlerin oldukça altındadır. Proses boyunca pH'ın 9,73'ten TSF çıkışında 8,19 seviyesine inmesi, hidrojen siyanür (HCN) volatilizasyonu riskini

ortadan kaldırırken, bu pH aralığının ICMM (2020) tarafından önerilen 8–10 güvenlik aralığıyla tamamen uyumlu olduğu görülmektedir.

Ayrıca proses süreci boyunca bakır (Cu) konsantrasyonunda belirgin bir düşüş gözlenmiş ve TSF çıkışındaki değerler çevresel limitlerin altında kalmıştır. Bu durum, metal-siyanür komplekslerinin detoksifikasyon aşamalarında etkin şekilde parçalandığını göstermektedir. TSF çevresinde yer alan piezometre kuyularında siyanür, tespit sınırının altında bulunmuş; bu bulgu, tesisin kullandığı çok katmanlı jeosentetik sızdırmazlık sistemlerinin yüksek etkinliğini ortaya koymuştur.

Sonuç olarak, madende uygulanan detoksifikasyon-nötralizasyon-TSF bütünleşik yönetim zinciri, siyanürlü proses atıklarının çevresel açıdan güvenli ve kontrol edilebilir şekilde yönetilmesini sağlamaktadır. Elde edilen bulgular, uluslararası uygulamalarla uyumlu, sürdürülebilir ve güvenilir bir siyanür yönetim modeli sunduğunu doğrulamaktadır.

Çalışma yalnızca tek saha ile sınırlıdır; farklı jeokimyasal koşullara sahip diğer altın işletmelerinde benzer analizler yapılmalıdır. Ölçümler belirli dönemleri kapsamaktadır; mevsimsel değişim ve ekstrem yağış koşullarının etkileri ayrıca değerlendirilmelidir. Bu çalışmada biyolojik izleme yapılmamıştır. Gelecek araştırmalarda, sucul ekosistem göstergeleri (besin ağlarının temeli olarak önemli bir rol oynayan mikroskobik, tek hücreli organizmalar) ile siyanür kalıntılarının etkileri incelenmelidir.

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ATIK BARAJLARINDA KULLANILACAK KİL MALZEMELERİN GEOTEKNİK ÖZELLİKLERİNİN DEĞERLENDİRİLMESİ

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ÖZET

Atık barajlarında sedde çekirdeği veya kil örtü malzemesi olarak kullanılacak zeminlerin uygunluğunun belirlenmesi, tesislerin uzun dönemli performansı ve çevresel güvenliği açısından kritik bir gerekliliktir. Bu tür yapılarda kullanılacak kil malzemelerinin düşük geçirgenlik göstermesi, yeterli plastisiteye sahip olması ve sahada yeterli derecede sıkıştırılabilirlik özellikleri sunması beklenir. Bu çalışmada, İstanbul bölgesindeki farklı jeolojik birimlerden temin edilen kil numuneleri üzerinde Atterberg limitleri, standart Proktor sıkıştırma deneyleri ve düşen seviyeli geçirgenlik testleri gerçekleştirilmiştir. Yapılan deneysel değerlendirmeler sonucunda, yüksek plastisiteli (CH) ve orta plastisiteli (CI) kil sınıflarındaki numunelerin plastisite indisi değerlerinin ($PI \geq 15$) atık depolama yapılarında aranan minimum gereksinimleri sağladığı belirlenmiştir. Bu numuneler, optimum su muhtevası ve maksimum kuru birim hacim ağırlığı değerleri açısından da uygun sıkıştırılabilirlik davranışı sergilemiş; laboratuvar koşullarında elde edilen düşük hidrolik geçirgenlik katsayıları ($k \approx 10^{-9}$-10^{-10} m/s) ile sedde çekirdeği ve kil astarı uygulamalarında kullanılabilir nitelikte bulunmuştur. Buna karşın, orta plastisiteli silt (MI) sınıfındaki bir numunenin plastisite özelliklerinin sınıra yakın değerlerde olduğu, sıkıştırma sonrası elde edilen geçirgenlik değerlerinin ise kabul edilebilir seviyelerin üzerinde ($k > 10^{-9}$ m/s) kaldığı tespit edilmiştir. Bu durum, söz konusu malzemenin tek başına bir kil çekirdeği veya kil astarı olarak kullanılmasının riskli olabileceğini göstermektedir. Elde edilen tüm deneysel veriler, uluslararası kılavuzlar ve tasarım dokümanlarında önerilen sınır değerlerle uyumluluk göstermekte; çalışma, malzeme seçiminde plastisite, kompaksiyon davranışı ve geçirgenlik parametrelerinin birlikte değerlendirilmesinin zorunluluğunu ortaya koymaktadır. Ayrıca saha kompaksiyon kontrolünün baraj güvenliği açısından vazgeçilmez bir unsur olduğu vurgulanmaktadır.

Anahtar Kelimeler: Atık barajı, Kil astarı, Geçirgenlik, Atterberg limitleri, Proktor deneyi.

EVALUATION OF GEOTECHNICAL PROPERTIES OF CLAY MATERIALS FOR USE IN TAILINGS STORAGE FACILITIES

ABSTRACT

Determining the suitability of soils to be used as core material or clay liner in tailings storage facilities is essential for ensuring the long-term performance and environmental safety of these structures. Clay materials selected for such applications are required to exhibit low hydraulic conductivity, adequate plasticity, and favorable compaction characteristics. In this study, clay samples collected from various geological units within the Istanbul region were subjected to Atterberg limits tests, Standard Proctor compaction tests, and falling-head permeability experiments. Experimental evaluations indicated that samples classified as high-plasticity clays (CH) and medium-plasticity clays (CI) meet the minimum design requirements for tailings dam construction. These samples possessed plasticity index (PI $\geq$ 15) values consistent with international guidelines, demonstrated appropriate compaction behavior in terms of optimum moisture content and maximum dry density, and yielded low hydraulic conductivity coefficients ($k \approx 10^{-9}$-10^{-10} m/s), confirming their suitability for use as core or clay liner materials.

Conversely, one sample classified as a medium-plasticity silt (MI) exhibited borderline plasticity characteristics and produced permeability values exceeding acceptable limits ($k > 10^{-9}$ m/s) even after compaction. This finding suggests that the silt material may pose risks if used alone as a core or liner without stabilization or blending with higher-plasticity clays. Overall, the experimental results align well with threshold values recommended by international design manuals and regulatory documents. The study highlights the critical importance of simultaneously evaluating plasticity, compaction response, and hydraulic conductivity during material selection. It also emphasizes that proper field compaction control remains indispensable for ensuring the structural integrity and environmental performance of tailings dam containment systems.

Keywords: Tailings dam, Clay liner, Permeability, Atterberg limits, Proctor compaction.

1. GİRİŞ

Cevher zenginleştirme tesisi atıklarının güvenli yönetimi, son on yılda meydana gelen yıkıcı kazalar ve artan yasal/toplumsal baskılar nedeniyle küresel ölçekte kritik bir mühendislik alanı hâline gelmiştir. UNEP'in "Safety is No Accident" raporu (2017), 2014 Mount Polley ve 2019 Brumadinho felaketlerinin ardından, atık depolama tesislerinde (TSF) tasarım-işletme-kapatma süreçlerinin bütüncül şekilde yeniden ele alınmasını zorunlu kılmıştır. Bu bağlamda oluşturulan Küresel Atık Yönetimi Standardı (ICMM, 2020), tüm TSF'lerde "sıfır zarar ilkesi"ni benimsemiş, düşük geçirimli bariyerlerin (kil çekirdek, kil kaplama, kil astar) tasarım ve kalite kontrolünde izlenebilir süreci zorunlu hâle getirmiştir (Al-Mahbashi vd., 2021; Karademir, 2022).

Cevher zenginleştirme tesisi atıkları; sülfür mineralleri, ağır metaller, kullanılan kimyasallar ve yüksek iyonik kuvvetli çözeltiler içermeleri nedeniyle, çevresel açıdan son derece agresif bir karakter sergilemektedirler. 2020 sonrası literatür, özellikle ağır metal taşınımına ilişkin risklerin hidrolik iletkenlik kadar kimyasal etkileşim süreçleriyle (iyon değişimi, flokülasyon, dispersiyon, şişme-çökelme davranışı) belirlendiğini göstermektedir (Hamdi ve Srasra, 2013; Özçoban vd., 2017; Widomski vd., 2021; Liu vd., 2023; Guduru vd., 2024). Bu nedenle, TSF alt yapılarında kullanılan doğal zeminlerin yalnızca düşük permeabilite sağlaması yeterli değildir; aynı zamanda kimyasal dayanım ve adsorpsiyon kapasitesinin de değerlendirilmesi gerekmektedir.

Son yıllarda araştırmalar, yüksek iyonik özellikli çözeltilerin kompakte kil astarların yapısal bütünlüğünü bozabileceğini ve hidrolik iletkenliği artırabileceğini göstermiştir (Xu vd., 2018; Ma vd., 2023). Örneğin, Cu(II) içeren yüksek konsantrasyonlu atık çözeltileri, killerde çift tabaka sıkışması ve flokülasyon etkisiyle permeabilitenin artmasına neden olabilmektedir. Bu nedenle birçok çalışma, kil astarların performansını geliştirmek amacıyla doğal zeolit (ör. klinoptilolit), organik polimerler (Na-PAA) ve yan ürün katkıları (uçucu kül, red mud, laterit) gibi malzeme modifikasyonlarının etkilerini incelemiştir (Kalkan, 2023; Zhang vd., 2025; Wang vd., 2025). Bu yeni nesil katkılar sayesinde hem hidrolik iletkenlik düşürülmekte hem de ağır metal adsorpsiyon kapasitesi artırılmaktadır. 2025 yılında yayımlanan kapsamlı bir çalışma, klinoptilolit ve Na-PAA ile zenginleştirilmiş kompakte kil astarların, Cu(II) içeren çözeltiler altında %78'e varan hidrolik iletkenlik azalması ve %65'e varan ağır metal adsorpsiyon kapasitesi artışı sağladığını ortaya koymuştur (Bi vd., 2025). Benzer şekilde, Zambiya'da yürütülen bir araştırma, doğal killerin 10^{-10} m/s mertebesindeki geçirimsizlikleri sayesinde TSF astarları için uygun bir ekonomik alternatif sunabileceğini göstermiştir (Brobbey vd., 2024).

Bununla birlikte, literatürün işaret ettiği önemli bir boşluk, kompakte kil astarların performansının saha koşullarındaki uzun dönemli davranışıdır. Yüksek iyonik kuvvet, değişken pH, redoks koşulları ve konsolidasyon basıncı gibi etkiler altında, laboratuvar performansı ile saha performansı arasında ciddi farklılıklar olabilmektedir. Bu nedenle, ICMM (2020), ANCOLD (2019), MAC/CDA (2021) ve TS EN 13491 gibi kılavuzlar, TSF tasarımında yalnızca laboratuvar deneylerine değil, saha kompaksiyon kontrolüne, mineralojik analizlere, kimyasal dayanım testlerine ve hidrolik iletkenliğin zaman-bağımlı izlenmesine vurgu yapmaktadır.

Sonuç olarak, güncel literatür açıkça göstermektedir ki:

- Kil astarların performansı yalnızca permeabilite ile ölçülemez; kimyasal dayanım ve adsorpsiyon kapasitesi kritik belirleyicilerdir.

- Cevher zenginleştirme tesisi atıkları, yüksek iyonik yükleri nedeniyle klasik kil astarların yapısını bozabilmekte; modifiye astarlar giderek zorunlu hâle gelmektedir.
- Doğal ve modifiye killer, jeomembranlarla birlikte hibrit bariyer sistemlerinde giderek daha fazla önerilmektedir.
- Sürdürülebilir madencilik için TSF bariyer tasarımı, reaktif taşınım modelleri ve uzun dönemli performans değerlendirmesi gerektirir.

Bu bağlamda çalışmanın amacı, laboratuvar ortamında elde edilen Atterberg limitleri, Proktor kompaksiyon parametreleri ve düşen seviyeli permeabilite test sonuçlarına dayanarak, inceleme konusu killerin cevher zenginleştirme tesisi atık barajlarında kompakte kil astar malzemesi olarak mühendislik açıdan uygunluğunu çok boyutlu şekilde değerlendirmektir.

2. MALZEME VE YÖNTEM

2.1. Çalışma Malzemeleri ve Numune Hazırlığı

Bu çalışmada, İstanbul ilindeki farklı jeolojik birimlerden temin edilen, atık depolama tesislerinde kullanılabilecek kil kökenli zeminlerin teknik uygunluğunu belirlemek amacıyla farklı plastisite ve mineralojik bileşime sahip 13 adet doğal kil numunesi değerlendirilmiştir. Numuneler laboratuvara getirildikten sonra etüv kurusu şartında hazırlanmış, tüm deneylerde standartlarda tarif edilen tane iriliği, su muhtevası ve numune hazırlanma prosedürleri esas alınmıştır.

Her bir kil numunesi için üç temel deney grubu uygulanmıştır:

1. Atterberg Kıvam Limitleri Deneyi (TS 1900-1; ASTM D4318)
2. Zemin Sıkıştırma (Proktor) Deneyi (TS 1900-1; ASTM D698)
3. Düşen Seviyeli Yöntem ile Hidrolik Geçirgenlik Tayini (TSE CEN ISO/TS 17892-11; DIN 18130; ASTM D5084 referanslı yöntem)

Bu deneyler, numunelerin plastisite davranışını, kompaksiyon özelliklerini ve hidrolik iletkenliğini bütüncül bir yaklaşımla değerlendirmek üzere gerçekleştirilmiştir. Deneylerde kullanılan cihazlardan bazıları Şekil 1’de verilmiştir.



(a) (b) (c)

Şekil 1. Deneylerde kullanılan cihazlar. (a-Proktor deney seti, b-Düşen seviyeli permeabilite deney seti, c-Likit limit cihazı).

2.2. Atterberg Limitleri ve Zemin Sınıflandırması

Her numune için likit limit (LL), plastik limit (PL) ve büzülme limiti (BL) deneyleri TS 1900-1 standardına uygun şekilde yapılmış; plastisite indisi PI = LL - PL bağıntısıyla hesaplanmıştır. Elde edilen değerler, numunelerin USCS sınıflandırmasına göre CH (yüksek plastisiteli kil), CI (orta plastisiteli kil) ve MI (orta plastisiteli silt) sınıflarına ayrılmasında kullanılmıştır. TSF tasarım literatüründe önerilen PI ≥ 15 sınırı (ICMM-GISTM, ANCOLD, MAC/CDA) malzeme uygunluğu için temel kriter olarak dikkate alınmıştır.

2.3. Zemin Sıkıştırma (Proktor) Deneyi

Numunelerin optimum sıkıştırma özellikleri, TS 1900-1 ve ASTM D698 Standart Proktor yöntemine göre belirlenmiştir. Her bir kil numunesi için, optimum su muhtevası (w_{opt}) ve maksimum kuru birim hacim ağırlığı ($\gamma_{d,max}$) kompaksiyon eğrilerinden elde edilmiştir.

TSF uygulamalarında yaygın olarak kullanılan ≥%95 $\gamma_{d,max}$ ve w_{opt} ± %2 saha kriterleri göz önünde bulundurularak geçirgenlik deneylerinde kullanılacak numuneler aynı kompaksiyon hedeflerinde hazırlanmıştır.

2.4. Hidrolik Geçirgenlik (Permeabilite) Deneyleri

Numunelerin doygun koşullar altındaki su geçirgenlikleri, Düşen Seviyeli (Falling-Head) yöntem kullanılarak, TSE CEN ISO/TS 17892-11 ve DIN 18130 standartlarına uygun biçimde belirlenmiştir.

Deney sürecinde, numuneler proktor yoğunluklarına göre sıkıştırılmış, esnek membranlı hücre içerisinde doygunlaştırılmış ve hidrolik iletkenlik (permeabilite) katsayısı (k), klasik düşen seviye denklemiyle (Denklem 1) hesaplanmıştır.

$$k = 2{,}3 * a * L / (A*t) * \log(h_2/h_1) \quad (1)$$

Burada ;

k: Hidrolik iletkenlik (permeabilite) katsayısı (m/s)

A: Numunenin Yüzey Alanı (m^2)

a: Hortum Alanı (m^2)

L: Numune Yüksekliği (m)

h_1: İlk Okuma (mm)

h_2: Son Okuma (mm)

t: Süre (saniye)

TSF tasarım kriterlerinde kabul edilen eşik değerler:

- Kil astarlarda: $k \leq 1\times10^{-9}$ m/s
- TSF kil çekirdeklerinde: $k \approx 10^{-9} – 10^{-8}$ m/s

olarak dikkate alınmıştır.

2.5. Veri Analizi ve Uygunluk Değerlendirme Yaklaşımı

Her deney sonucunun TSF tasarım kriterlerine uygunluğu, aşağıdaki üç temel parametreye göre yapılmıştır:

1. Plastisite Uygunluğu ($PI \geq 15$)
2. Kompaksiyon Uygunluğu ($\geq$%95 $\gamma_{d,max}$ ve w_{opt} aralığı)
3. Geçirgenlik Uygunluğu ($k \leq 10^{-9}$ m/s)

Bu üç kriter birlikte ele alınarak numunelerin “kil çekirdek”, “kil astar” veya “uygun değil/koşullu” kategorilerine yerleştirilmesi için karar matrisi altyapısı oluşturulmuştur.

3. BULGULAR

Bu bölümde, kil numunelerine ait Atterberg limitleri, kompaksiyon parametreleri ve geçirgenlik deney sonuçları bütüncül olarak değerlendirilmiştir. Deneysel bulgular, Tablo 1’de sunulan veriler üzerinden yorumlanmıştır.

Tablo 1. Kil numunelerine ait Atterberg limitleri, kompaksiyon parametreleri ve geçirgenlik sonuçları.

No	LL	PL	BL	PI	Sınıf	$\gamma_{d,max}$ (g/cm³)	w_{opt} (%)	k (m/s)
1	68,0	25,7	15,0	42,3	CH	1,43	25,5	$7,27\times10^{-10}$
2	53,0	27,0	18,0	26,0	CH	1,48	27,2	$1,15\times10^{-9}$
3	45,0	29,7	23,0	15,3	MI	1,56	16,6	$1,22\times10^{-9}$
4	43,0	25,4	19,0	17,6	CI	1,63	18,6	$1,16\times10^{-9}$
5	75,0	30,7	18,0	44,3	CH	1,50	24,6	$6,04\times10^{-10}$
6	57,0	28,1	18,0	28,9	CH	1,47	26,0	$1,24\times10^{-9}$
7	53,0	27,9	19,0	25,1	CH	1,48	27,3	$2,87\times10^{-10}$
8	69,0	33,4	17,0	38,6	CH	1,35	33,2	$3,31\times10^{-10}$
9	51,0	24,2	16,0	26,8	CH	1,46	25,2	$2,35\times10^{-10}$
10	56,0	25,6	17,0	30,4	CH	1,47	24,2	$2,39\times10^{-10}$
11	57,1	28,4	18,0	28,7	CH	1,39	27,1	$2,47\times10^{-10}$
12	55,3	27,9	18,0	27,4	CH	1,42	26,0	$2,59\times10^{-10}$
13	54,1	25,0	17,0	29,1	CH	1,51	26,5	$3,24\times10^{-10}$

Açıklamalar: LL: Likit Limit, PL: Plastik Limit, BL: Büzülme Limiti, PI: Plastisite İndisi, $\gamma_{d,max}$: Maksimum Kuru Birim Hacim Ağırlığı, W_{opt}: Optimum Su Muhtevası, k: Hidrolik İletkenlik, CH: Yüksek plastisiteli kil; CI: Orta plastisiteli kil; MI: Orta plastisiteli silt.

3.1. Atterberg Limitleri ve Zemin Sınıflandırması

Numunelerin likit limit (LL), plastik limit (PL) ve plastisite indisi (PI) değerleri Tablo 1'de verilmiştir. Bu sonuçlara göre; 13 numunenin 11'i CH (yüksek plastisiteli kil) sınıfında, 1'i CI (orta plastisiteli kil) sınıfında ve 1 numune de MI (orta plastisiteli silt) sınıfındadır.

Plastisite indisleri:

- CH killer için PI = 25-44 aralığındadır.
- CI sınıfındaki numune (No: 4) PI = 17,6 ile minimum mühendislik eşiğine yakındır.
- MI sınıfındaki numune (No: 3) PI = 15,3 ile sadece sınır değerin üzerindedir.

TSF kil çekirdeği ve astarı için literatürde önerilen PI ≥ 15 kriteri incelendiğinde 12 numunenin uygun olduğu açıkça görülmektedir. Sadece MI sınıfında olan bir numunenin düşük plastisite nedeniyle sınır değerde uygunluk gösterdiği görülmüştür. Bu sonuçlar, yüksek PI değerine sahip killerin çatlama ve iç erozyon direnci açısından daha avantajlı olduğunu desteklemektedir.

3.2. Kompaksiyon Davranışı (w_{opt} - $\gamma_{d,max}$)

Deney sonuçlarına göre maksimum kuru birim hacim ağırlıkları ($\gamma_{d,max}$) 1,35 – 1,63 g/cm³ arasında değişmektedir. wopt değerleri de CH killerde %24 - 33 aralığında, MI numunesinde

%16,6, CI numunesinde ise %18,6 olarak belirlenmiştir. Bu dağılım, plastisite arttıkça optimum su içeriğinin artması şeklindeki klasik davranışı doğrulamaktadır.

TSF uygulamalarında kritik olan ≥%95 $\gamma_{d,max}$ ve w_{opt} ± %2 saha şartları göz önüne alındığında: tüm numuneler sıkıştırılabilirlik açısından kabul edilebilir mühendislik özellikleri göstermektedir. MI numunesi düşük su içeriği ile silt karakteri sergilemekte olup kompakte edildiğinde geçirgenlik yönünden daha riskli bir davranış gösterebilir.

3.3. Hidrolik Geçirgenlik (k) Sonuçları

Düşen seviyeli permeabilite deneyleri sonucunda numunelerin k değerleri $2{,}35\times10^{-10}$ m/s ile 1×10^{-9} m/s arasında değişmektedir. TSF tasarım kriterleri açısından $k \leq 1\times10^{-9}$ m/s olan tüm numuneler kil astarında kullanılabilir niteliktedir. CH grubu killerin çoğu $k \leq 5\times10^{-10}$ m/s mertebesinde olup yüksek mühendislik performansı göstermektedir. MI sınıfındaki numune ise PI değerine paralel olarak üst sınırda bir geçirgenlik sergilemektedir.

4. SONUÇLAR

Bu çalışma kapsamında değerlendirilen kil numunelerinin Atterberg limitleri, kompaksiyon davranışları ve hidrolik geçirgenlik özellikleri birlikte ele alındığında, zeminlerin atık barajlarında (TSF) kompakte kil çekirdeği veya kil astarı olarak kullanılabilirliklerini belirleyen mühendislik kriterleri açısından önemli bulgular elde edilmiştir. Bulgular, hem klasik geoteknik prensiplerle hem de güncel uluslararası standartlarla büyük ölçüde uyumludur.

Plastisite, kompaksiyon ve geçirgenlik özellikleri birlikte değerlendirildiğinde; yüksek uygunluk kategorisindeki killer (CH), $PI \geq 25$, $k \leq 5\times10^{-10}$ m/s (çoğunluk), w_{opt} - $\gamma_{d,max}$ değerleri saha şartlarıyla uyumlu olduğu için TSF kil çekirdek ve astar uygulamaları için yüksek uygunluk göstermektedir. Koşullu uygunluk sınıfına giren killer (CI), PI = 17,6 (sınır üstü), k = 1×10^{-9} m/s (üst eşik) olduğundan astar olarak kullanılabilir, çekirdek için projeye bağlı olarak değerlendirilmelidir. Sınırda uygunluk sınıfına giren zemin numuneleri (MI), PI = 15,3 (minimum eşik), k = 1×10^{-9} m/s (üst eşik), Silt karakteri özelliği olduğundan tek başına çekirdek/astar için önerilmez; katkı veya karışım gerektirir.

Her ne kadar laboratuvar sonuçları TSF uygulamaları için güçlü bir uygunluk gösterse de literatürde sıkça belirtilen bazı uzun dönem performans riskleri göz önünde bulundurulmalıdır:

- Islanma-kuruma döngüleri kil matrisinde mikro çatlaklara neden olabilir.
- Yüksek iyonik konsantrasyonlu atık çözeltileri (Cu^{2+}, Fe^{3+}, SO_4^{2-} vb.) çift tabakayı sıkıştırarak permeabiliteyi artırabilir.
- Drenaj gradyanı yüksek çekirdek bölümlerinde iç erozyon riski artabilir.

Bu nedenle, uygun malzemenin seçilmesine ek olarak TSF tasarımında: (i) filtre zonlarının doğru yerleştirilmesi, (ii) saha kompaksiyon kontrolü, (iii) uzun dönem hidrolik izleme programları tasarımın ayrılmaz bir parçası olmalıdır.

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SU BAZLI BİYO-POLİÜRETANLAR İÇİN BİYO-POLİESTER POLİOLLERİN GELİŞTİRİLMESİ

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ÖZET

Su bazlı biyo-poliüretanlar için geliştirilen biyo-poliester polioller, sürdürülebilir malzeme üretimine önemli bir katkı sağlamaktadır. Poliüretanlar (PU'lar), yüksek mekanik dayanım, kimyasal direnç ve düşük sıcaklıklarda esneklik gibi üstün özelliklerinden dolayı endüstriyel uygulamalarda yaygın olarak kullanılmaktadır. Ancak geleneksel olarak solvent bazlı sistemlerin kullanımı, çevresel ve sağlık riskleri oluşturduğundan, özellikle uçucu organik bileşik (VOC) emisyonlarının artması, alternatif çözücü sistemlerin geliştirilmesini zorunlu hale getirmiştir. Bu doğrultuda, su bazlı PU dispersiyonları (WPUD), çevreye daha dost bir seçenek olarak öne çıkmakta ve son yıllarda yapılan araştırmalarda su bazlı sistemler üzerine yoğunlaşılmaktadır. Bu çalışmada, biyo-poliester poliollerin sentezi, doğal kaynaklardan elde edilen sebasik asit (SA) ve süksinik asit (SUA) gibi biyolojik kökenli diasitler kullanılarak gerçekleştirilmiştir. Poliollerin lineer yapısının oluşturulmasında dietilen glikol (DEG) ve 1,6 heksandiol (HDO) gibi alifatik dioller tercih edilmiştir. Kondenzasyon polimerizasyonu, vakum altında ve herhangi bir çözücü kullanılmadan, sıcaklık kontrollü cam bir reaktörde mekanik karıştırma ile yürütülmüştür. Sentez sırasında, asit grubunun tüketimini artırmak amacıyla glikolün 1:1,15 mol oranında fazlası eklenmiştir. Elde edilen poliester poliollerin yapısal karakterizasyonu Fourier dönüşümlü kızılötesi spektroskopi (FTIR) ile doğrulanmış; C=O ve C-O ester bantlarının varlığı ile poliester oluşumu teyit edilmiştir. Moleküler ağırlık parametreleri ise jel geçirgenlik kromatografisi (GPC) ile belirlenmiş ve polidispersite indeksi (PDI) değerleri polimerin moleküler ağırlığı dağılımını yansıtmıştır. Ayrıca, sentez tepkimesi ilerlemesi asit sayısı takibiyle izlenmiştir. Araştırmada kullanılan biyolojik kökenli hammaddeler ve solventsiz tepkime ortamı, süreç boyunca çevre dostu bir yaklaşımın benimsendiğini göstermektedir. Sonuç olarak, elde edilen biyo-poliester polioller hem sürdürülebilirlik hem de fonksiyonellik açısından su bazlı biyo-PU uygulamalarında ileri teknolojilere katkı sunmaktadır. Bu çalışmanın, çevreye duyarlı PU üretiminde biyobazlı hammaddelerin daha etkin kullanımı için yol gösterici nitelik taşıdığı ve yeni nesil su bazlı PU sistemlerinin geliştirilmesinde önemli bir referans olacağı söylenebilir.

Anahtar Kelimeler: Biyo poliol, Sebasik Asit, Süksinik Asit, Su Bazlı Poliüretan

GİRİŞ

Su bazlı poliüretanlar (WPU'lar), poliüretan parçacıklarının sürekli bir sulu faz içinde dağıtıldığı kolloidal dispersiyonlardır. Bu sistemlerin ana bileşenleri mükemmel kolloidal stabilite gösterir ve suda kolayca dağılır, bu da diğer kolloidal parçacıklar veya katkı maddeleriyle daha fazla fonksiyonelleştirmeyi kolaylaştırır (Honarkar, 2018).

WPU sentezinde polioller, temel öncüller olarak hizmet eder ve polimerin nihai özelliklerini belirlemede belirleyici bir rol oynar. Yaygın olarak kullanılan polioller arasında polieter, polyester ve polikarbonat türleri bulunur. Polieter bazlı WPU'lar esneklikleri, hidrolitik stabiliteleri ve uygun maliyetleriyle bilinirler, ancak oksijene ve ışığa duyarlılıkları nedeniyle uzun vadeli dayanıklılıkları ve çözücü dirençleri sınırlıdır. Polyester bazlı WPU'lar ise üstün yağ ve çözücü direnci sunar, ancak hidrolitik koşullar altında daha az kararlı olma eğilimindedirler. Polikarbonat bazlı polioller, mükemmel mekanik mukavemet ve hidrolize, yağa ve çevresel bozulmaya karşı direnç sağlar, ancak diğer ikisine kıyasla nispeten pahalıdırlar (Mehravar vd., 2019; Cakić vd., 2013).

Farklı poliol türleri arasında polyester polioller, mükemmel termal kararlılık, alev geciktiricilik ve solvent direncine sahip PU malzemelerin üretiminde önemli bir rol oynar. Polieter bazlı sistemlere kıyasla hidrolize karşı daha az dirençli olmalarına rağmen, polyester polioller yüksek performanslı PU elastomerlere, esnek köpüklere, yapıştırıcılara ve kaplamalara önemli ölçüde katkıda bulunur. Ayrıca, polyesterler, yenilenebilir ve sürdürülebilir malzemelere yönelik artan küresel vurguyla uyumlu olarak, biyobazlı poliüretanların sentezi için umut verici öncüller olarak kabul edilir (Mahmood vd., 2016; Ionescu, 2005; Choffat vd., 2023).

Geleneksel olarak oligomerik polioller fosil bazlı hammaddelerden sentezlenir. Ancak, bu yenilenemeyen kaynakların tükenmesi ve artan sera gazı emisyonları, biyobazlı poliollerin sürdürülebilir alternatifler olarak geliştirilmesini teşvik etmiştir. Sebasik asit (SA) türevi polyester polioller en çok incelenen örnekler arasındadır. SA, öncelikle bol miktarda bulunan, ucuz ve yenilenebilir bir hammadde olan hint yağından elde edilir. Uzun alifatik zincir yapısı sayesinde SA bazlı polyesterler, PU malzemelerin mekanik, termal ve yapışkan performansını artıran yüksek kristallik ve erime noktalarına sahiptir (Mokhtari vd., 2018; Li vd., 2020; Umare vd., 2007). Son çalışmalar ayrıca SA'nın polikarbonat bazlı reaktif poliüretan sıcak eriyen yapıştırıcılarda biyoasit bileşeni olarak başarılı bir şekilde kullanıldığını bildirmiştir (Sun vd., 2023). Bir diğer önemli yenilenebilir monomer ise şekerlerin fermantasyonu yoluyla üretilebilen süksinik asittir (SUA). Özellikle diğer yenilenebilir monomerlerle birleştirildiğinde, tamamen biyobazlı malzemelerin sentezlenmesi için ideal bir biyo-yapı taşıdır (Jacquel vd., 2011; Jiang vd., 2017).

Bu çalışmada, SA ve SUA gibi yenilenebilir diasitler kullanılarak biyobazlı polyester polioller sentezlenmiştir. Lineer polimer omurgasını oluşturmak için dietilen glikol (DEG) ve 1,6-heksandiol (HDO) dahil olmak üzere alifatik dioller seçilmiştir. Elde edilen poliollerin kimyasal yapıları Fourier dönüşümlü kızılötesi spektroskopisi (FTIR) ile doğrulanırken, moleküler ağırlık parametreleri jel geçirgenlik kromatografisi (GPC) kullanılarak belirlenmiştir. Sentezlenen polimerlerin moleküler ağırlık dağılımını değerlendirmek için polidispersite indeksi (PDI) değerleri kullanılmıştır. Bu çalışma sürdürülebilir su bazlı poliüretan sistemlerinin hazırlanmasına uygun biyobazlı polyester poliollerin geliştirilmesi ve karakterizasyonu ile çevre dostu polimer malzemelerin ilerlemesine katkıda bulunmayı amaçlamaktadır.

MATERYAL ve YÖNTEM

Materyal

Çalışma kapsamında, Sebasik asit (ticari derece, >= %99,0), süksinik asit(teknik derece, >= %99,0), dietilen glikol (ticari derece, >= %95,0-99,0), 1,6-heksandiol (ticari derece, >= %95,0-99,0), ve butil stannoik asit (ticari derece, >= %95,0-99,0) belirtilen saflıklarda kullanılmıştır.

Poliollerin Sentezi

Sentez tepkimesi için kullanılan sistem, geri soğutuculu, mekanik karıştırıcılı, ısıtma ve soğutmanın birlikte kullanılabildiği, vakum ortamında, sıcaklık kontrollü bir cam polimerizasyon reaktöründen oluşmaktadır. Hazırlanan dört farklı Poliester Poliol (PEO) Tablo 1'deki gibi adlandırılmış olup, Karboksil: Hidroksil (COOH:OH) oranları 1:1,15 olarak sabit tutulmuştur.

Tablo 1. Poliester Poliollerin Bileşimleri.

Örnek Kodu	Örnek Bileşimi	COOH:OH
PEO-1	SA:DEG	1:1,15
PEO-2	SA:HDO	1:1,15
PEO-3	SUA:DEG	1:1,15
PEO-4	SUA:HDO	1:1,15

Karakterizasyon

Katı madde yüzdesi, ASTM D2369'a göre numunenin 110°C'de 1 saat ısıtılmasıyla belirlendi. Sentezlenen polyester poliollerin asit sayısı, ASTM D4662 test yöntemine göre ölçüldü. Numunelerin kimyasal yapısı, 4000–600 cm^{-1} ölçüm aralığına sahip bir Shimadzu Corp. Iraffinity-1S FTIR Spektrometresi üzerinde zayıflatılmış toplam yansıma cihazı kullanılarak FTIR spektrometrisi kullanılarak incelendi.

Moleküler ağırlık parametreleri (¯Mw ve ¯Mn) ve polidispersite indeksi (PDI; ¯Mw/¯Mn), bir Tosoh EcoSEC HLC-8320GPC sistemi kullanılarak belirlendi. Ayırma işlemi için, TSKgel 5000HXL, G4000HXL ve G3000HXL kolonlarıyla birlikte bir TSKgel HXL-L koruyucu kolon kullanıldı. Sistem hem kırılma indisi hem de UV-Vis dedektörleriyle donatılmış olup, GPC düzeneğine bir Waters-Wyatt Technology WTREOS-15 çok açılı ışık saçılım dedektörü de bağlanmıştır. HPLC sınıfı tetrahidrofuran, seyreltici olarak ve polimer çözeltilerinin hazırlanmasında kullanılmıştır.

BULGULAR ve TARTIŞMA

Sentezlenen poliester poliollerin % katı madde miktarı, asit sayısı ölçümleri Tablo 2'de özet olarak verilmiştir. Buna göre poliester poliollerin tamamı %1'den az oranda su içermektedir. Vakum altında gerçekleşen reaksiyonlar su çıkışı gerçekleşmeyene kadar sürdürülmüştür. Sentez sonrası ölçülen asit sayıları sebasik asit kullanılan poliolllerde (PEO-1 ve PEO-2) 12 mgKOH/g olarak ölçülürken, süksinik asit kullanılan poliollerde (PEO-3 ve PEO-4) sırasıyla 9 ve 3 mgKOH/g olarak ölçülmüştür.

Tablo 2. Poliester Poliollerin Özellikleri.

Örnek Kodu	Fiziksel Görünüm (@25°C)	Katı Madde (%)	Asit Sayısı (mgKOH/g)
PEO-1	Katı	99,3	12
PEO-2	Katı	99,0	12
PEO-3	Sıvı	99,7	9
PEO-4	Katı	99,4	2

Şekil 1. Sentezlenen polyester poliollerin FTIR spektrumunu göstermektedir. Elde edilen FTIR sonuçlarına göre, polyester poliollerdeki alifatik düz zincir titreşimlerinin ($–CH_2–$) karakteristik tepe noktaları sırasıyla 2800–3000 cm^{-1}'de görülmektedir (Saltan ve Akat, 2021). PEO spektrumlarında 1722 cm^{-1}'de görülen absorpsiyon bandı ve 1157 cm^{-1} civarındaki bir diğer tepe noktası, esterin fonksiyonel grupları (–COOH) ve (C–O) grupları olan karboksil grubunun karakteristik absorpsiyon tepe noktası olan (C=O)'ya atfedilebilir (Tang vd., 2006). 1100–1200 cm^{-1} aralığındaki çoklu emilim tepe noktası, kullanılan poliollerden türetilen ester gruplarından kaynaklanan (C(O)-O-C) gerilme titreşimiyle ilişkilidir (Parcheta vd., 2020).

GPC analizleri sonucunda PEO-3 poliolü ile yapılan sentezler haricinde birbirine yakın sonuçlar elde edilmiştir. Bu da hedeflenen yapıların sentezlendiğini kanıtlamaktadır. SA'nın kullanıldığı PEO-1 ve PEO-3 poliollerinin molekül ağırlığı SUA'nın kullanıldığı poliollerden yüksek değerlerde ölçülmüştür (Tablo 3). PDI'ı 1,05-1,2 olarak ölçülen POE numuneleri monodispers (tek molekül ağırlıklı) yapıdadır.

Tablo 3. Poliester Poliollerin Moleküler Özellikleri.

Örnek Kodu	Mw (g/mol)	Mn (g/mol)	PDI (Mw/Mn)
PEO-1	3266	2857	1,143
PEO-2	2983	2823	1,056
PEO-3	7141	5975	1,195
PEO-4	3351	3013	1,112

SONUÇLAR

Bu çalışmada, biyo-POE'lerin sentezi, SA ve SUA gibi biyolojik kaynaklı diasitler kullanılarak gerçekleştirilmiştir. POE'lerin yapısının oluşturulmasında DEG ve HDO gibi alifatik dioller kullanılmıştır. Elde edilen poliester poliollerin yapısal karakterizasyonu FTIR ile doğrulanmış; 1722 cm^{-1}'de görülen absorpsiyon bandı ve 1157 cm^{-1} civarındaki bir diğer tepe noktası, C=O ve C-O ester bantlarının varlığı ile poliester oluşumu teyit edilmiştir. Moleküler ağırlık parametreleri GPC ile belirlenmiş ve PDI değerlerinde poliollerin moleküler ağırlığı dağılımının monodispers olduğu görülmüştür. Özetle, geliştirilen biyo-poliester polioller, hem sürdürülebilirlik hedeflerine hizmet etmekte hem de su bazlı biyo-PU uygulamalarında işlevsellik açısından ileri düzey çözümler sunmaktadır.

KATKI

Bu bildiri, birinci sırada yer alan yazarın Kocaeli Üniversitesi, Fen Bilimleri Enstitüsü'nde hazırladığı yayımlanmamış doktora tezinden üretilmiştir. Ayrıca çalışma, 1002-A/224Z160 TÜBİTAK projesi kapsamında hazırlanmış ve desteklenmiştir.

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SUSTAINABLE ALTERNATIVE CORROSION INHIBITORS FOR ENGINE COOLANT FLUIDS

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ABSTRACT

One of the most critical components determining the performance of coolants used in the engine cooling system is the corrosion inhibitor. While water and ethylene glycol provide effective heat transfer, they alone cannot prevent corrosion and wear on metal surfaces. Therefore, the use of suitable corrosion inhibitors is essential for the long-term efficiency and durability of the cooling system. In this study, the effectiveness of Organic Acid Technology (OAT)-based additives was investigated. The most commonly used OAT component is 2-ethylhexanoic acid. However, 2-ethylhexanoic acid has the GHS08 (health hazard) pictogram according to the harmonized classification and labelling system, which indicates that the substance is hazardous and may also damage the unborn child. Therefore, this study aims to investigate new carboxylic acid corrosion inhibitors that are more suitable for human health and the environment. In this context, isononanoic acid and a polycarboxylic acid were selected to be evaluated as new type corrosion inhibitors for engine cooling fluids. Separate formulations were prepared and tested individually for 2-ethylhexanoic acid, isononanoic acid and polycarboxylic acid to evaluate their corrosion protection performance. The results showed that all additives provided good corrosion protection. Among the developed corrosion inhibitor additives, the isononanoic acid and polycarboxylic acid-based additives stand out in terms of sustainability and environmental impact.

Keywords: Engine coolant, corrosion inhibitor, ethylene glycol, organic acid, non-hazardous additive.

INTRODUCTION

Antifreeze is a water-based coolant used in gasoline and diesel engines. All coolants are typically made from water, a base fluid such as ethylene glycol or propylene glycol, and various corrosion-inhibiting additives. Coolants serve three main functions: first, to remove heat from hot engine components to prevent overheating during operation; second, to prevent the coolant from freezing when the vehicle is not in use in cold climates; and third, to protect the metal components of the engine block and cooling system from corrosion. Automotive radiators are made of parts containing various metals that are electrochemically incompatible, such as aluminium, cast iron, copper, brass, and solder. Ethylene glycol or propylene glycol in the antifreeze tends to corrode these metals under high temperature and ventilation conditions in internal combustion engines. Therefore, corrosion inhibitors added to antifreeze are of great importance.

Automotive coolants are generally classified into three main technologies: Inorganic Additive Technology (IAT), Organic Acid Technology (OAT) and Hybrid Organic Acid Technology (HOAT). IAT coolants use traditional inorganic additives such as silicates and phosphates to protect engine metals, but they lose their effectiveness more quickly and must be replaced more often. OAT coolants use organic acids like carboxylates and 2-ethylhexanoic acid (2-EHA), providing longer-lasting protection, especially for modern aluminium radiators, although they are not suitable for older systems with **brass or soldered** parts. HOAT coolants combine both inorganic and organic additives, offering a balanced protection system and are commonly used in many recent vehicles. Finally, all information regarding the types of coolants is presented in Table 1.

Table 1. Coolant Type and Colour Chart [1].

TYPE	INHIBITOR TECHNOLOGY	COLOR	VEHICLES
IAT (Inorganic Additive Technology)	Silicates	Green	Older Vehicles
OAT (Organic Acid Technology)	Organic Acids	Orange	GM, Saab, VW
HOAT (Hybrid OAT)	Silicates & Organic Acids	Yellow	Ford, Chrysler, European
HOAT (Hybrid OAT, Phosphate-free)	NAP Free	Turquoise	BMW, Volvo, Tesla, Mini, others
P-HOAT (Phosphated HOAT)	Phosphates & Organic Acids	Pink / Blue	Toyota, Nissan, Honda, Hyundai, KIA & other Asian vehicles
Si-OAT (Silicated HOAT)	Silicates & Organic Acids	Purple	Mercedes-Benz, Audi, VW, Porsche, others

Water glycol-based cooling systems are prone to chemical and galvanic corrosion due to the presence of different metal alloys. Therefore, not only the antifreeze function but also the use of appropriate corrosion inhibitors is critical. Studies have shown that inhibitor packages

significantly reduce the corrosion rate on metals [2]. Chen et al. (2015) have developed organic acid-based antifreeze coolants to improve both corrosion protection and environmental compatibility in water–glycol cooling systems. These coolants not only inhibit metal corrosion effectively but also reduce the formation of deposits and sludge, enhancing system performance and longevity [3].

2-ethylhexanoic acid has the GHS08 (health hazard) pictogram according to the harmonized classification and labelling (ATP20) system, which indicates that the substance is hazardous and may also damage the unborn child. In contrast, isononanoic and polycarboxylic acid do not have such a hazard pictogram [4]. Therefore, they are more sustainable alternatives. The purpose of the study is to investigate new carboxylic acid corrosion inhibitors that are more suitable for human health. In this context, isononanoic acid and a polycarboxylic acid were selected to be evaluated as new type corrosion inhibitors for engine cooling fluids instead of 2-ethylhexanoic acid.

MATERIALS AND METHOD

Materials

In this study, 2-ethylhexanoic acid, isononanoic acid, and polycarboxylic acid were selected as additive components to evaluate their different corrosion-inhibiting performances. The other main component of the coolant formulation was monoethylene glycol with a purity of ≥99.9 wt%. In addition, NaOH (48 wt%) was used as a buffering agent.

Methods

All tests were performed in accordance with the relevant ASTM and DIN standards. The pH values of the samples were measured using a Mettler Toledo SD20 pH meter according to ASTM D 1287 [5]. Filter paper corrosion tests were carried out in accordance with the DIN 51360 standard [6]. Glassware corrosion tests were conducted according to ASTM D 1384 [7], and the results were evaluated against the tolerance limits specified in ASTM D 3306 [8].

Figure 1 shows an example of filter paper corrosion testing.

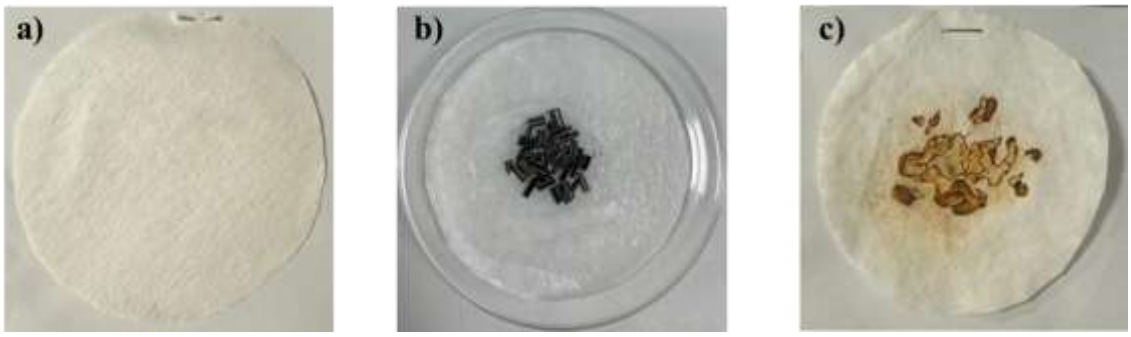

Figure 1. Filter paper corrosion test a) Filter paper before test, b) During Test and c) After testing (Corrosion present), DIN 51360.

Additionally, glassware corrosion testing has been performed on aluminium, cast iron, steel, copper, brass, and solder using a corrosion tester. The glassware corrosion tester and plates are shown in Figure 2.

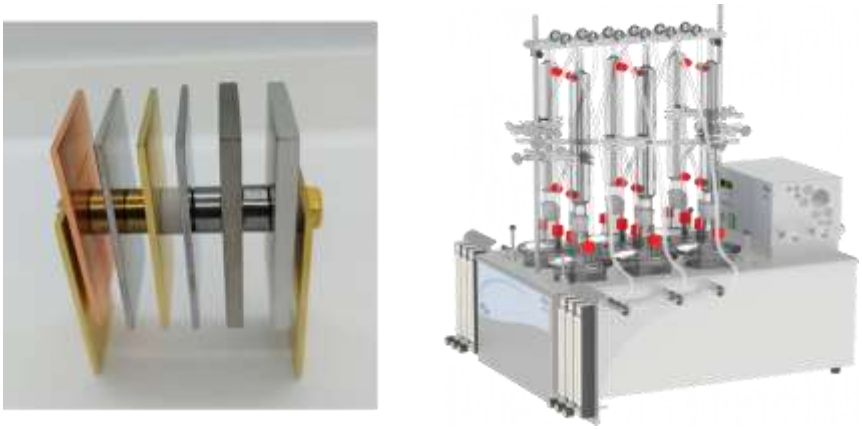

Figure 2. Corrosion test for engine coolants in glassware, ASTM D 1384.

Experiment

The experimental work utilized the compounds 2-ethylhexanoic acid, isononanoic acid, and polycarboxylic acid. First part, each compound was separately neutralized with sodium hydroxide (NaOH) to prepare stock solutions, which were stirred until homogeneous. Afterwards, the filter paper corrosion test was applied to these samples. In the second part, these stock solutions were subsequently diluted with water and subjected to a filter paper corrosion test to evaluate their inhibitory performance. Based on the results, the additive formulations demonstrating the highest corrosion resistance were identified. In the third part, these optimized formulations were then incorporated into antifreeze solutions. The antifreeze samples were prepared at three different concentrations 100%, 50%, and 33% (v/v) and evaluated through a series of tests, including filter paper corrosion, glassware corrosion, and other relevant performance assessments.

The structures of corrosion inhibitor components are given in Figure 3.

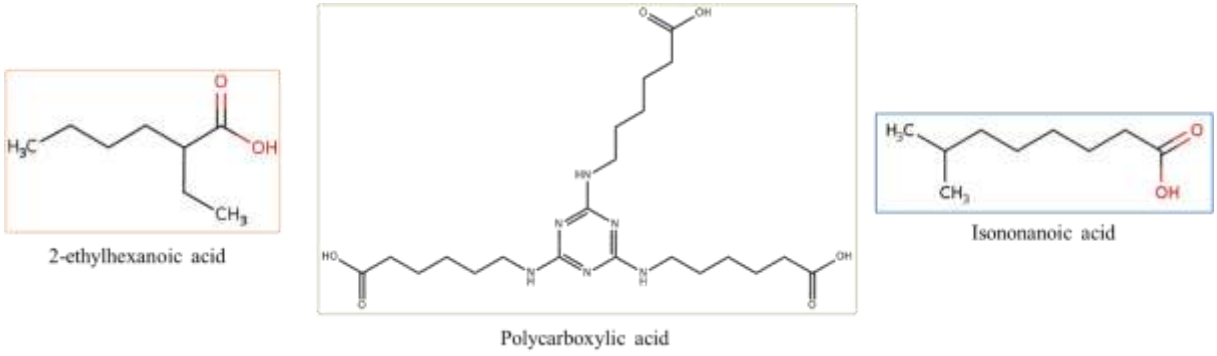

Figure 3. Molecular structures of the components that constitute the corrosion inhibitor

RESULTS AND DISCUSSION

To prevent potential corrosion in the final antifreeze formulation, pH and corrosion tests were performed on the diluted form of the 10% stock solution. Table 2 presents the pH and corrosion test results of the diluted 10% 2-ethylhexanoic acid stock solution. The filter paper corrosion test results for the 1% and 2% ratios of the stock solution are given in Figure 4. According to the results, 2-ethylhexanoic acid has shown good corrosion inhibition performance as is known.

Table 2. Test results for the diluted 10% 2-ethylhexanoic acid stock solution

Dilution Rates	pH	Filter Paper corrosion Test (24 hours)
%5 stock 2-EHA + water	13.16	No corrosion
%4 stock 2-EHA + water	13.1	No corrosion
%3 stock 2-EHA + water	13	No corrosion
%2 stock 2-EHA + water	12.85	Corrosion present
%1 stock 2-EHA + water	12.61	Corrosion present

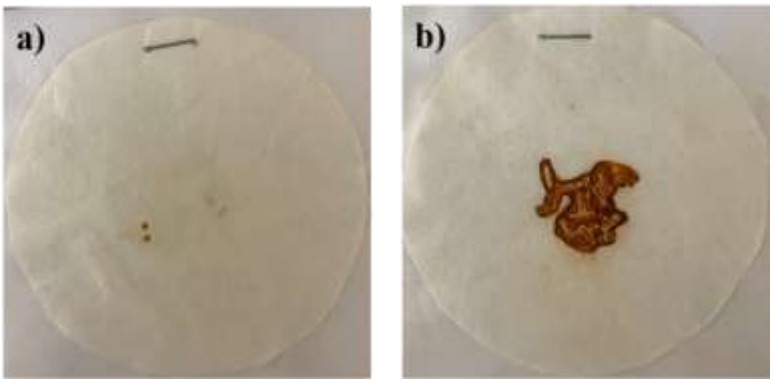

Figure 4. Corrosion test images for the a) 1% and b) 2% dilutions of the stock solution

The optimal ratios were selected, and water-diluted 2-ethylhexanoic acid-based additive formulations were prepared accordingly. The results of these formulations are presented in Table 3 and Figure 5, demonstrating their respective properties and performance.

Table 3. Dilution results of 2-ethylhexanoic acid-based additive

	pH	Filter Paper Corrosion Test (24 hours)
100% additive	9.23	No corrosion
50% diluted additive	9.19	No corrosion
33% diluted additive	9.11	No corrosion

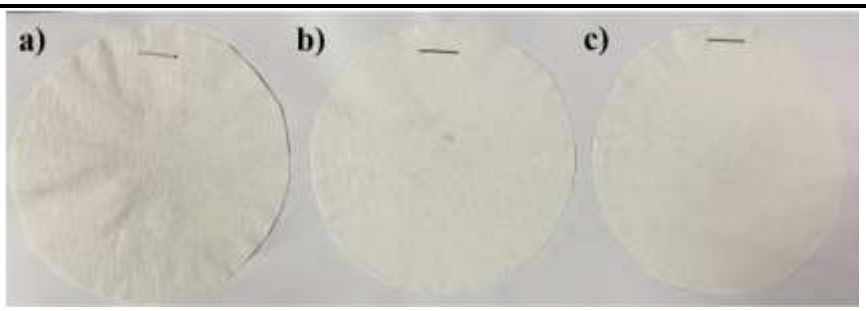

Figure 5. Filter paper corrosion test images for the a) 100% b) 50% and c) 33% dilutions of the additive

Subsequently, the study progressed to the final antifreeze formulation, and the corresponding test results are presented in Table 4 and Figure 6. The results indicate that the 2-ethylhexanoic acid-based additive can be used as a corrosion-inhibiting component in antifreezes.

Table 4. 2-ethylhexanoic acid-based antifreeze results

Antifreeze Ratio	pH	Filter Paper Corrosion Test (24 hours)
100% Antifreeze	7.7	No corrosion
50% Antifreeze	7.47	No corrosion
33% Antifreeze	7.51	No corrosion

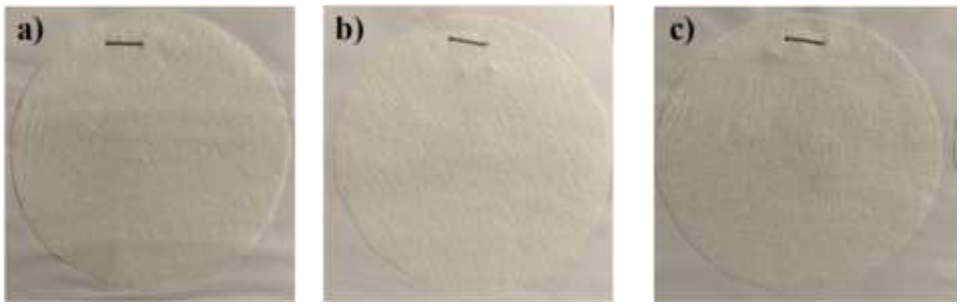

Figure 6. Filter paper corrosion test images for the a) 100% b) 50% and c) 33% antifreeze

To evaluate the corrosion inhibition performance of isononanoic acid and determine suitable dilution ratios, pH measurements and corrosion tests were carried out on various dilutions prepared from the 10% stock solution. Table 5 presents the pH values and corrosion test results of the 10% isononanoic acid stock solution diluted at different ratios. The results indicate that isononanoic acid provides effective corrosion inhibition as an additive, except at the 1% dilution ratio. The filter paper corrosion test result for the 1% dilution is shown in Figure 7.

Table 5. Test results for the diluted 10% Isononanoic acid stock solution

Dilution Rates	pH	Filter Paper corrosion Test (24 hours)
%5 stock Isononanoic acid + water	6.98	No corrosion
%4 stock Isononanoic acid + water	6.81	No corrosion
%3 stock Isononanoic acid + water	6.63	No corrosion
%2 stock Isononanoic acid + water	6.55	No corrosion
%1 stock Isononanoic acid + water	6.52	Corrosion present



Figure 7. Corrosion test images for the 1% dilution of the stock solution

After determining the optimal ratios, water-diluted isononanoic acid-based additive formulations were prepared accordingly. The results of these formulations, presented in Table 6 and Figure 8, indicate that isononanoic acid-based additive exhibits corrosion-inhibiting properties.

Table 6. Dilution results of Isononanoic acid-based additive

	pH	**Filter Paper Corrosion Test (24 hours)**
100% additive	9.37	No corrosion
50% diluted additive	9.18	No corrosion
33% diluted additive	9.11	No corrosion

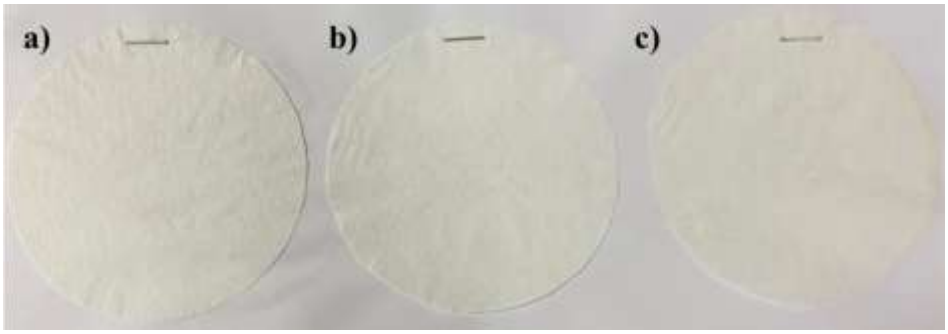

Figure 8. Filter paper corrosion test images for the a) 100% b) 50% and c) 33% dilutions of the additive

Subsequently, the study progressed to the final antifreeze formulation, and the corresponding test results are presented in Table 7 and Figure 9. The results indicate that the isononanoic acid-based additive can be used as a corrosion-inhibiting component in antifreezes.

Table 7. Isononanoic acid-based antifreeze results

Antifreeze Ratio	pH	Filter Paper Corrosion Test (24 hours)
100% Antifreeze	7.41	No corrosion
50% Antifreeze	7.6	No corrosion
33% Antifreeze	7.67	No corrosion

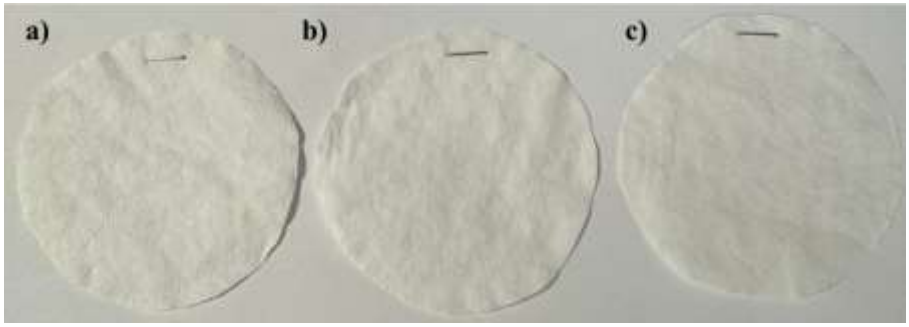

Figure 9. Filter paper corrosion test images for the a) 100% b) 50% and c) 33% antifreeze

Similarly, a formulation containing a lower ratio of the polycarboxylic acid additive was examined, and it exhibited excellent corrosion protection performance despite the reduced dosage. The results are presented in Table 8.

Table 8. 2% Polycarboxylic acid-based stock results

Dilution Rate	pH	Filter Paper Corrosion Test (24 hours)
%2 Polycarboxylic acid stock	8.02	No corrosion

The optimal ratio was selected, and water-diluted polycarboxylic acid-based additive formulations were prepared accordingly. The results are shown in Table 9 and Figure 10.

Table 9. Dilution results of Polycarboxylic acid-based additive

	pH	Filter Paper Corrosion Test (24 hours)
100% additive	8.02	No corrosion
50% diluted additive	7.99	No corrosion
33% diluted additive	7.96	No corrosion

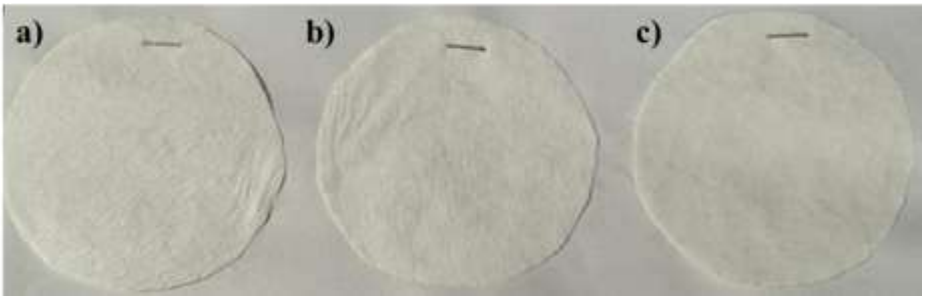

Figure 10. Filter paper corrosion test images for the a) 100% b) 50% and c) 33% dilutions of the additive

Following this step, the research advanced to the preparation of the final antifreeze formulation, with the relevant test outcomes provided in Table 10 and Figure 11. These findings demonstrate that the polycarboxylic acid-based additive is suitable for use as a corrosion-inhibiting agent in antifreeze applications.

Table 10. Polycarboxylic acid-based antifreeze results

Antifreeze Ratio	pH	Filter Paper Corrosion Test (24 hours)
100% Antifreeze	7.71	No corrosion
50% Antifreeze	7.98	No corrosion
33% Antifreeze	8.02	No corrosion

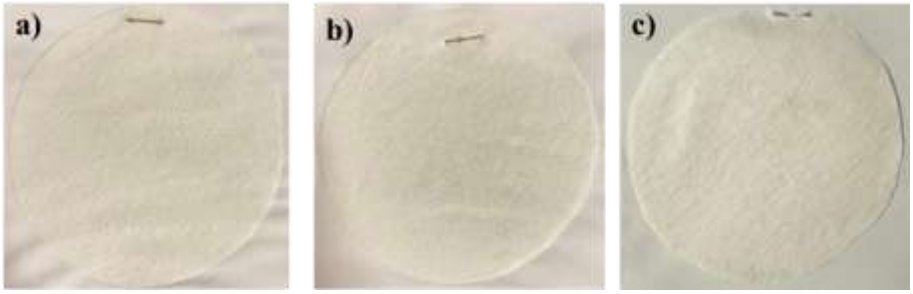

Figure 11. Filter paper corrosion test images for the a) 100% b) 50% and c) 33% antifreeze

In the final phase of the study, a glassware corrosion test, simulating actual operating conditions and involving components of a cooling engine, was conducted in accordance with the ASTM D 1384 standard. Metal parts from an automotive radiator were subjected to this test. The ASTM D 3306 method defines the maximum limit weight loss of metal parts due to corrosion. Negative results indicate the formation of a protective layer on the surface. The lower the weight loss of the metal coupons, the higher the anticorrosion performance. As shown in Table 11, the 2-ethylhexanoic acid-based antifreeze successfully passed this test.

Table 11. 2-ethylhexanoic acid-based antifireeze glasware corrosion results

ASTM D 1384 Test			**ASTM D 3306 Limit**
Plates	**Weight Loss (mg/cm^2)**	**Weight Loss (mg/specimen)**	**Weight Loss (mg/specimen)**
Copper (C11000)	0.2989	7.8	10 max
Solder (Grade 30A (30/70 Sn/Pb))	0.0651	1.7	30 max
Brass (C26000)	-0.0574	-1.5	10 max
Steel (SAE 1020)	0.0153	0.4	10 max
Cast Iron (G3500)	-0.0766	-2	10 max
Cast Aluminum (A23190)	-0.0766	-2	30 max

The experimental results obtained according to the ASTM D 1384 method are presented in Table 12. The isononanoic acid-based additive also exhibited corrosion protection in this test, which simulated the conditions of an actual cooling system.

Table 12. Isononanoic acid-based antifireeze glasware corrosion results

ASTM D 1384 Test			**ASTM D 3306 Limit**
Plates	**Weight Loss (mg/cm^2)**	**Weight Loss (mg/specimen)**	**Weight Loss (mg/specimen)**
Copper (C11000)	0.0192	0.5	10 max
Solder (Grade 30A (30/70 Sn/Pb))	0.5596	14.6	30 max
Brass (C26000)	-0.0115	-0.3	10 max
Steel (SAE 1020)	-0.0537	-1.4	10 max
Cast Iron (G3500)	-0.0767	-2	10 max
Cast Aluminum (A23190)	-0.0153	-0.4	30 max

CONCLUSION

In summary, the corrosion tests showed that all developed additives possess excellent corrosion-inhibiting properties. The filtration corrosion tests and glassware corrosion tests conducted in this study demonstrated that the developed additives exhibit stable performance and good compatibility with antifreeze formulations used in the automotive industry. The positive outcomes obtained from these tests support the suitability of the additives for key metals commonly found in automotive radiators, such as aluminium, cast iron, copper, brass, and solder.

Although 2-ethylhexanoic acid remains an effective component in antifreeze formulations, recent safety assessments highlight the need to explore safer alternatives. Since 2-EHA is classified under certain risk categories within the ECHA Hazard Classification and Labelling

System, evaluating alternative substances that are not classified as hazardous under ECHA has gained importance. In this context, the findings indicate that isononanoic acid and polycarboxylic acid represent potential alternatives to 2-ethylhexanoic acid, as they are not classified as hazardous and offer a more favourable safety profile.

Overall, the results of this study provide a scientific basis for transitioning to new-generation antifreeze additives that ensure both effective corrosion protection and improved safety, offering valuable guidance for future development efforts.

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IMPROVEMENT OF BOUNDARY LUBRICATION CHARACTERISTICS WITH DIFFERENT ESTER TYPES

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ABSTRACT

It is known that ester-based additives reduce friction and protect surfaces from wear under boundary lubrication conditions due to their strong surface affinity. These properties contribute to extending the operational life of machine components. In this study, the effects of different ester types, such as Methyl Oleate, 2-Ethylhexyl Oleate, Pentaerythritol Monooleate (PEMO), Trimethylolpropane Trioleate (TMPTO), Diisotridecyl Adipate (DTDA), Zinc Dialkyldithiophosphate (ZDDP) and Triphenyl Phosphorothionate (TPPT) on the improvement of boundary lubrication characteristics were investigated using a linear oscillation SRV (Schwingung, Reibung, Verschleiss) tribometer. For this purpose, all ester types were blended into the Group I mineral base oil at 10 wt%. However, TPPT was used at 5 wt% due to its limited miscibility. The viscosity of all formulations was kept within a similar range to ensure a fair comparison. According to the lubrication regime graph, only the first 10 minutes of the SRV friction curves were considered in the evaluation. The results revealed that Diisotridecyl Adipate and phosphate esters significantly enhance boundary lubrication performance by reducing friction between the metal ball and disc. In contrast, monoesters exhibited limited or even adverse effects on friction behavior. Overall, this study demonstrates the critical importance of ester type selection for optimizing boundary lubrication performance and shows that the molecular structure of the esters has a significant influence on boundary lubrication mechanisms.

Keywords: Lubrication, boundary lubrication, ester additives, tribology, friction

1. INTRODUCTION

Tribology is the science that studies the interactions of surfaces in contact and in relative motion. Generally, tribology includes three key topics: friction, wear and lubrication. Friction is the resistance to relative motion, wear is the loss of material due to that motion, and lubrication Additionally, wear leads to material loss and decreased mechanical performance. Lubrication is the use of a fluid or in some cases a solid to minimize friction and wear. (Mischler S.)

In modern engineering systems, machines operate at increasingly higher speeds, causing contacting surfaces to experience severe friction and substantial wear. Elevated friction leads to unnecessary energy losses and negatively affects the durability and service life of critical components. The resulting decline in performance within production systems also poses significant risks to operational reliability and quality consistency. Therefore, in high-technology applications, controlling friction and wear has become essential for improving overall efficiency and ensuring long-term system stability. (T, 2021)

Tribological data is commonly presented in the form of a Stribeck curve.(Meyer F.) The Stribeck curve is a graph of the friction coefficients according to the Hersey number (Bearing number) (Spikes H., 1997). The Hersey number is a dimensionless number of rotational velocity, external force, and viscosity of the lubricant. It divides the frictional properties of a rotor and bearing system into three lubricating regions of hydrodynamic, mixed, and boundary lubrications. (Hong G., 2022)

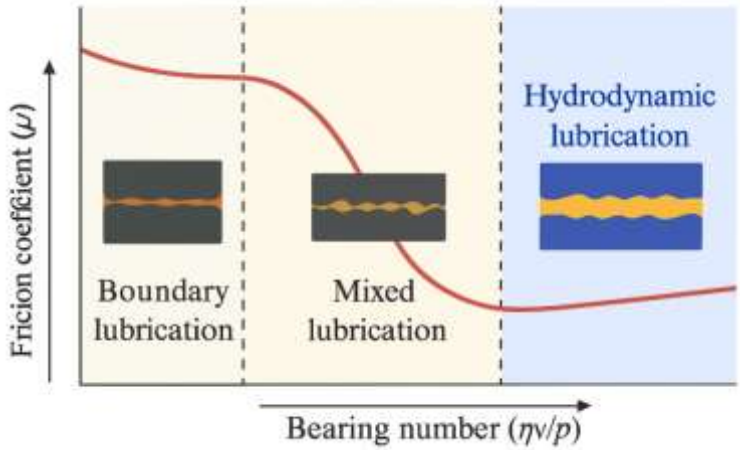


Figure 1. Streibeck curve (Li S., 2023)

At sufficiently high sliding speeds, the lubricant is drawn into the contact and forms a pressurized fluid layer that completely separates the two surfaces; film thickness increases with viscosity and speed, and decreases with load. Wear is negligible in this case, and this condition is referred to as hydrodynamic lubrication.

When the speed is lower or the load is higher, the fluid film becomes thin enough to approach the surface roughness. Part of the load is still carried by the fluid layer, but some asperity contact occurs, leading to limited wear; this regime is known as mixed lubrication.

At very low speeds and high loads, a continuous fluid film cannot be sustained, and the full load is transmitted through direct asperity contact. Significant wear takes place, although adsorbed lubricant molecules may still offer partial protection; this situation is called boundary lubrication. (Mischler S.) Since the lubricant film can no longer prevent direct surface

interactions, chemical additives become the primary mechanism for reducing friction and wear. In other words, the performance of the system becomes highly dependent on how effectively the lubricant molecules can adsorb onto the surface and form protective boundary layers.

Ester-based additives play a particularly important role under these conditions. Due to their polar functional groups, esters exhibit strong affinity for metallic surfaces, enabling them to adsorb and create a stable, coherent film that reduces metal-to-metal contact. This adsorbed layer can lower the coefficient of friction and serve as a sacrificial barrier, preventing direct asperity interactions and minimizing wear.

In addition to their surface activity, esters offer several inherent advantages for boundary lubrication. Their molecular structure typically provides good thermal stability, allowing them to retain lubricity at elevated temperatures where many hydrocarbon-based components begin to degrade. Furthermore, esters are often characterized by high biodegradability, making them attractive for environmentally conscious formulations, especially in applications where lubricant loss to the environment is likely. Their tunable viscosity and strong solvency also improve additive compatibility and overall formulation stability.

Recent studies report that monoesters, diesters, and polyol esters have all been evaluated as boundary lubrication agents, with several works employing SRV-type oscillating tribometers to assess their friction and wear behavior. These findings consistently show that ester-based structures can significantly enhance boundary lubrication through strong surface adsorption and stable film formation. In this context, Mofidi M. conducted SRV oscillation tests under a 100 N load to evaluate the friction and wear behavior of different ester classes, including monoesters, diesters, and polyol esters. His findings demonstrated clear differences in film formation and surface protection among these ester types, further emphasizing that ester chemistry plays a decisive role in boundary lubrication performance. (M., 2007)

Fox et al. investigated the boundary lubrication effects of free fatty acids by doping sunflower oil with stearic, oleic, and linoleic acids. They found that saturated stearic acid delivered the strongest friction- and wear-reducing performance, while the unsaturated acids showed noticeably weaker improvement under boundary conditions. (Fox N.J., 2003)

In the present study, the boundary lubrication performance of various ester structures was systematically examined by blending into a mineral base oil and evaluating their friction-reducing capabilities during the initial stages of SRV oscillation testing.

2. EXPERIMENTAL METHOD

In this study, Group I mineral oils SN-500 (Heavy Neutral) and SN-900 (Bright Stock) are mixed to be used as base fluids. Their physicochemical properties were given in Table 1.

Table 1. Physicochemical properties of base fluids.

Test Parameter	**Test Method**	**SN-500**	**SN-900**
Kinematic Viscosity (40°C, cSt)	ASTM D 445	99,773	504,8
Kinematic Viscosity (100°C, cSt)	ASTM D 445	10,84	30,42
Viscosity Index	ASTM D 2270	91	88
Flash Point (°C)	ASTM D 92	256	316
Pour Point (°C)	ASTM D 97	-6	-6

To investigate the influence of different ester structures on boundary lubrication performance, various ester types including Methyl Oleate, 2-Ethylhexyl Oleate, Pentaerythritol Monooleate (PEMO), Trimethylolpropane Trioleate (TMPTO), and Diisotridecyl Adipate (DTDA) were individually blended with the base oil mixture at predetermined ratios given in Table 1. Each formulation includes a single ester type along with SN-500 and SN-900 as base oils. To ensure a consistent comparison of tribological behavior across the ester-containing blends, all formulations were adjusted to achieve the same target viscosity level.

As a formulation describtion, the ester mass fractions and the final blend viscosities are provided in Table 2. All experiments were conducted with a 10 wt% ester addition, except for TPPT. This exception is due to the solid nature of TPPT, which did not allow adequate miscibility at the 10% level.

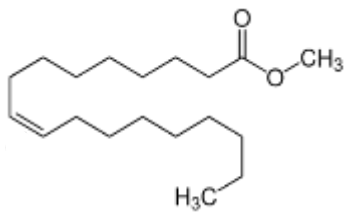
Table 2. Formulation Table

Product No	**Additives**	**Ester Ratio %by mass**	**Kinematic Viscosity of Final Blend (40°C, cSt)**
Pr. 1	Methyl Oleate	10	150
Pr. 2	2-Ethylhexyl Oleate	10	150
Pr. 3	PEMO	10	150
Pr. 4	TMPTO	10	150
Pr. 5	Diisotridecyl Adipate	10	150
Pr. 6	ZDDP	10	150
Pr. 7	TPPT	5	150

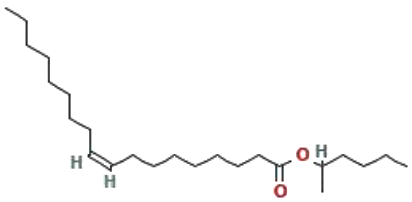
Molecular structures of Methyl Oleate, 2-Ethylhexyl Oleate, PEMO, TMPTO, Diisotridecyl Adipate, ZDDP, and TPPT were given in

Table ***3***.

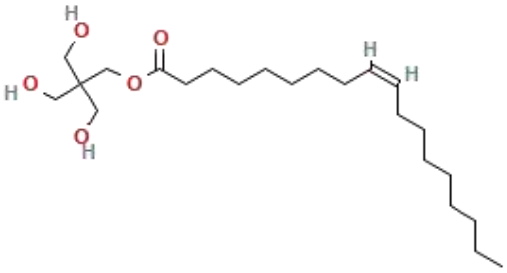
Table 3. Molecular Structures



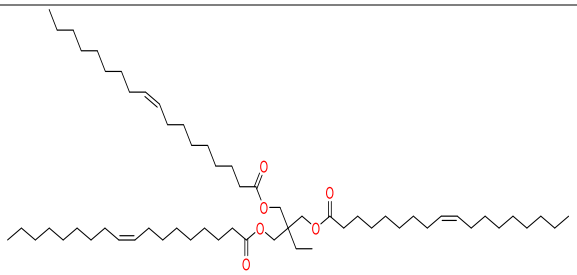
Methyl Oleate



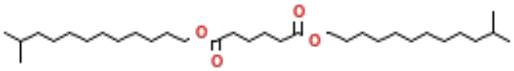
2-Ethylhexyl Oleate



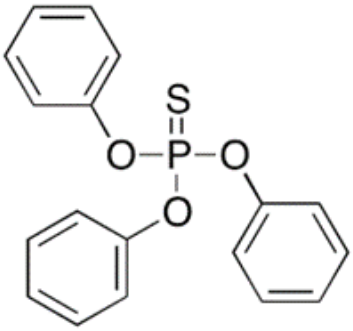
PEMO



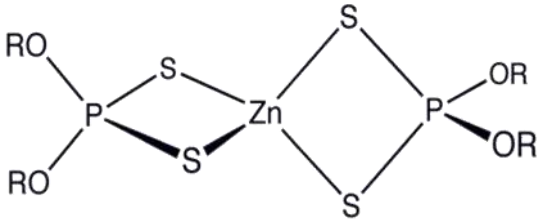
TMPTO



Diisotridecyl Adipate



TPPT



ZDDP

High Frequency Linear Oscillation – SRV (Schwingung, Reibung, Verschleiss)

SRV instrument, shown in Figure 2, is a well versatile laboratory machine that aims to evaluate friction and wear characteristics of lubricants in many different operative conditions by using couplings of different geometry and materials. In this work, the selected coupling is stainless steel cylinder on disk, and the procedure is ASTM D 6425.

The test values of the method are shown in Table 4.

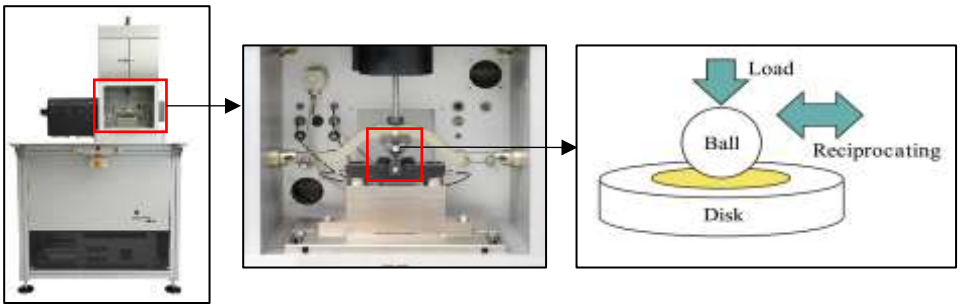


Figure 2. Optimol SRV tribometer

Table 4. ASTM D 6425 Method for determination of friction and wear properties

Test Parameters	**Test Conditions**
Temperature	50°C
Constant Load	300 N
Stroke	1 mm
Frequency	50 Hz
Time	120 min.
Ball Type	Steel-10mm

The SRV friction curves of the products will be evaluated as presented in Figure 2. As known from the Stribeck curve, the boundary lubrication regime corresponds to the initial stage in which the lubricant film is not yet able to fully separate the two metal surfaces. Since metal-to-metal contact is predominant in this region, the maximum friction values are observed here. The improvements provided by different ester types are therefore identified by whether they reduce the f_{max} value.

RESULTS

The boundary lubrication performance and friction coefficients of the formulations were evaluated using the ASTM D6425 method on an SRV tribometer. A complete 120-minute measurement table is presented in Figure 3. In addition, Figure 3 represents a Stribeck-type interpretation of the SRV test results, which models the coefficient of friction over time according to the lubrication regime. Since the boundary lubrication regime corresponds to approximately the first 30 minutes of all experiments, only this region of the friction curves was considered in the performance assessment and is depicted accordingly.

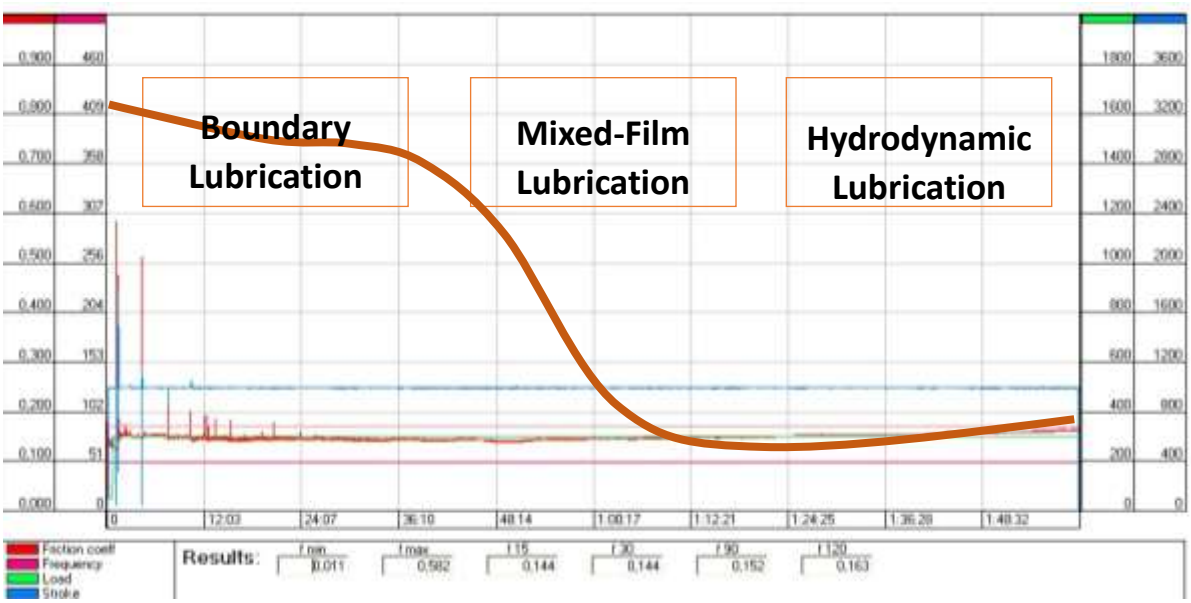


Figure 3. SRV test result evaluation according to Stribeck curve

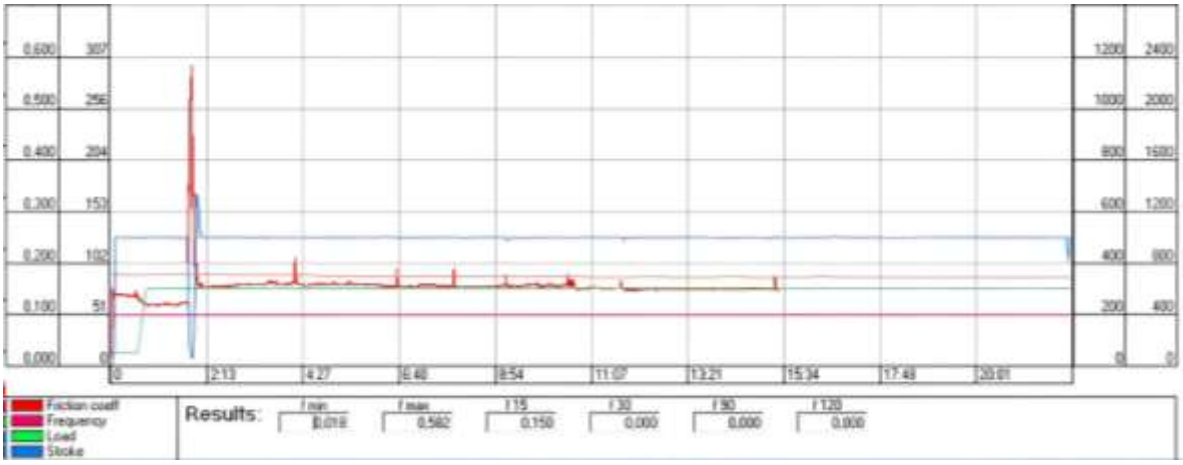


Figure 4. SRV chart of 150 KV @40°C with ASTM D 6425 method

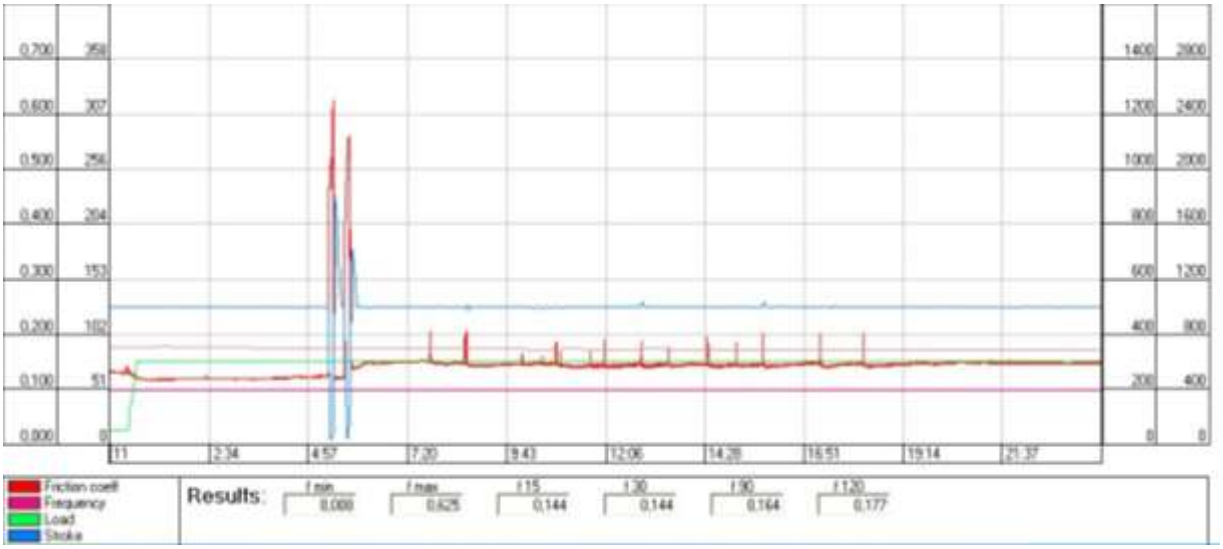


Figure 5. SRV chart of Methyl Oleate with ASTM D 6425 method



Figure 6. SRV chart of 2-Ethylexyl Oleate with ASTM D 6425 method

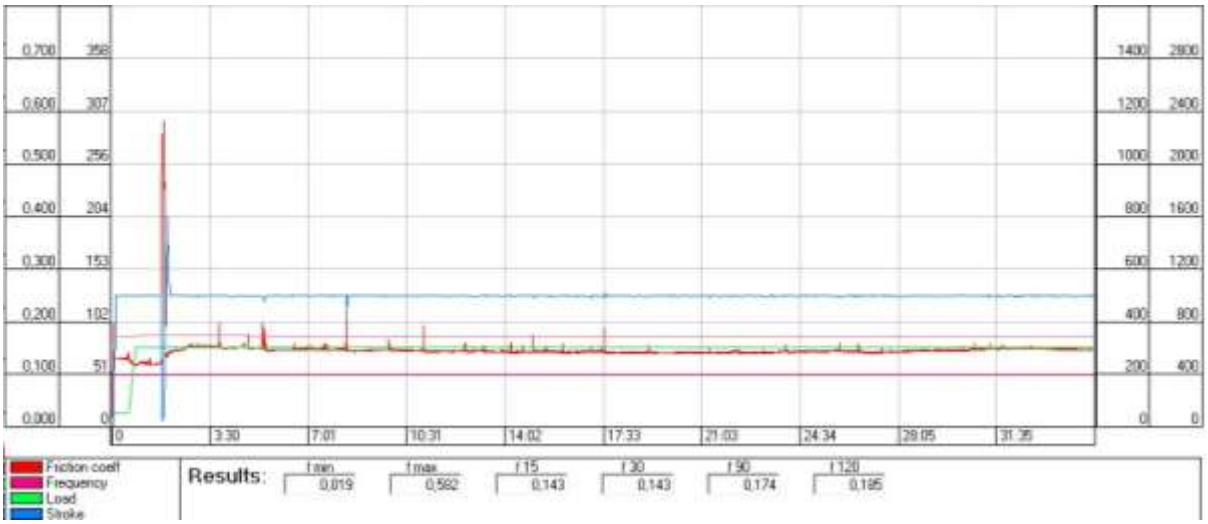


Figure 7. SRV chart of PEMO with ASTM D 6425 method

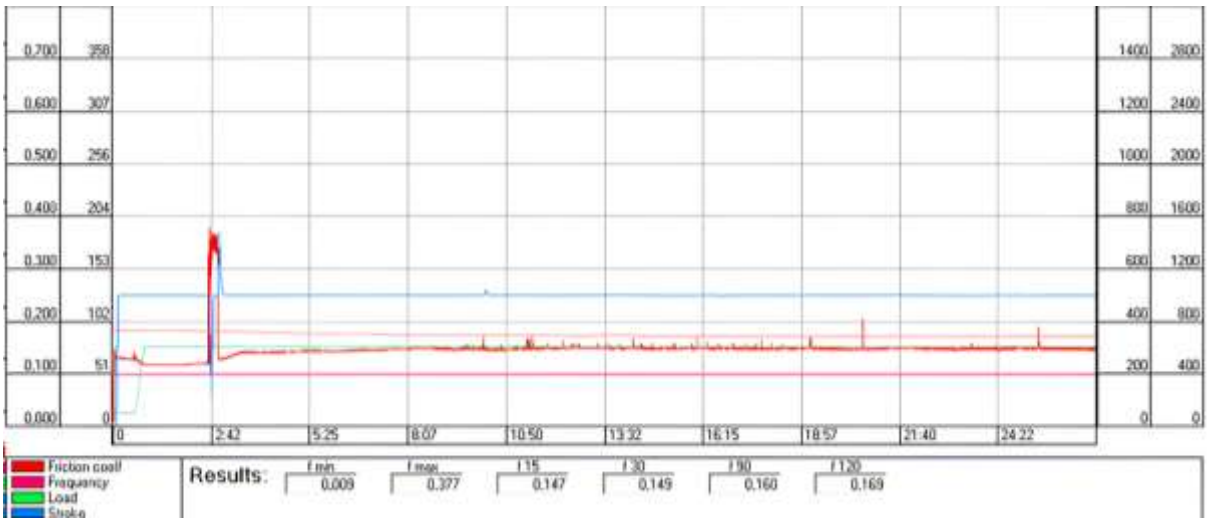


Figure 8. SRV chart of TMPTO with ASTM D 6425 method

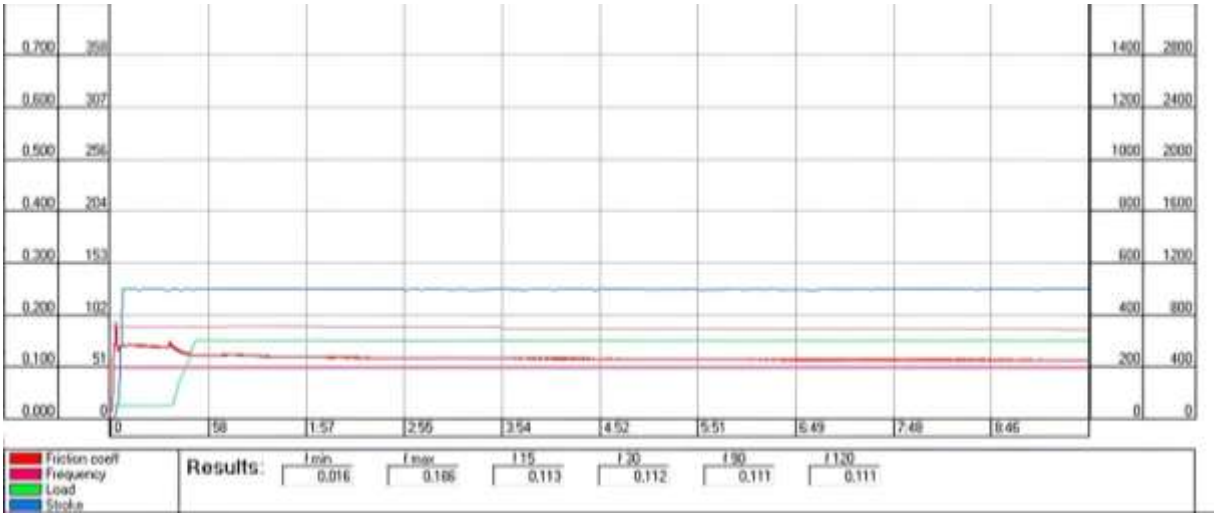


Figure 9. SRV chart of Diisotridecyl Adipate with ASTM D 6425 method

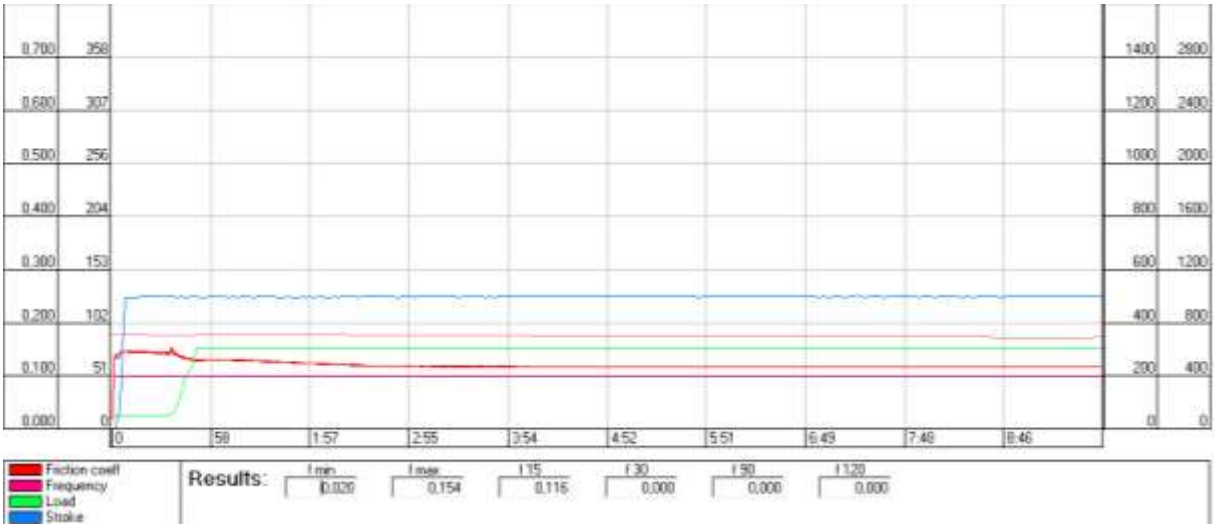


Figure 10. SRV chart of ZDDP with ASTM D 6425 method

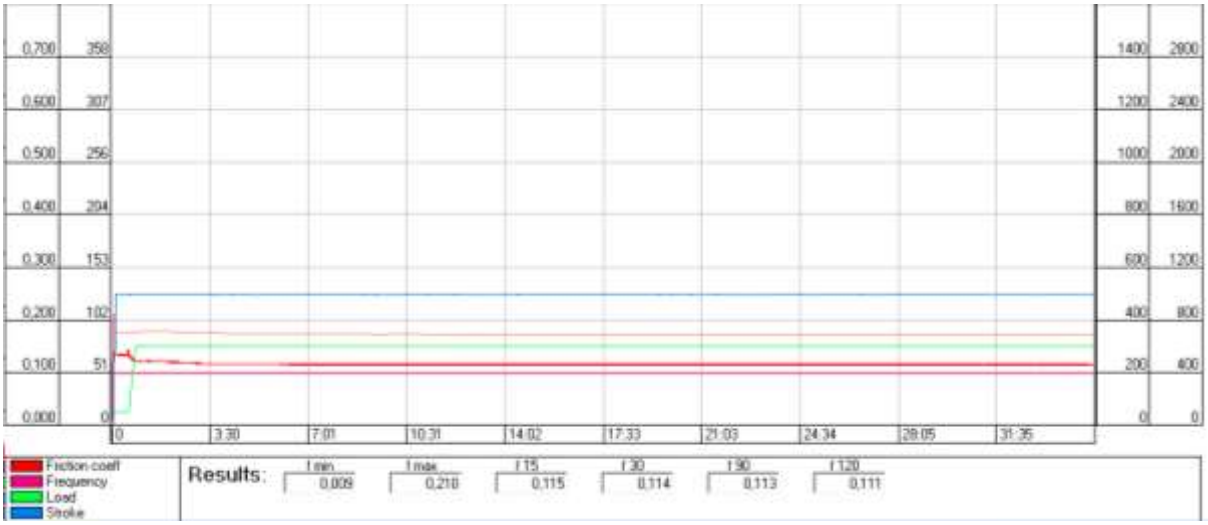
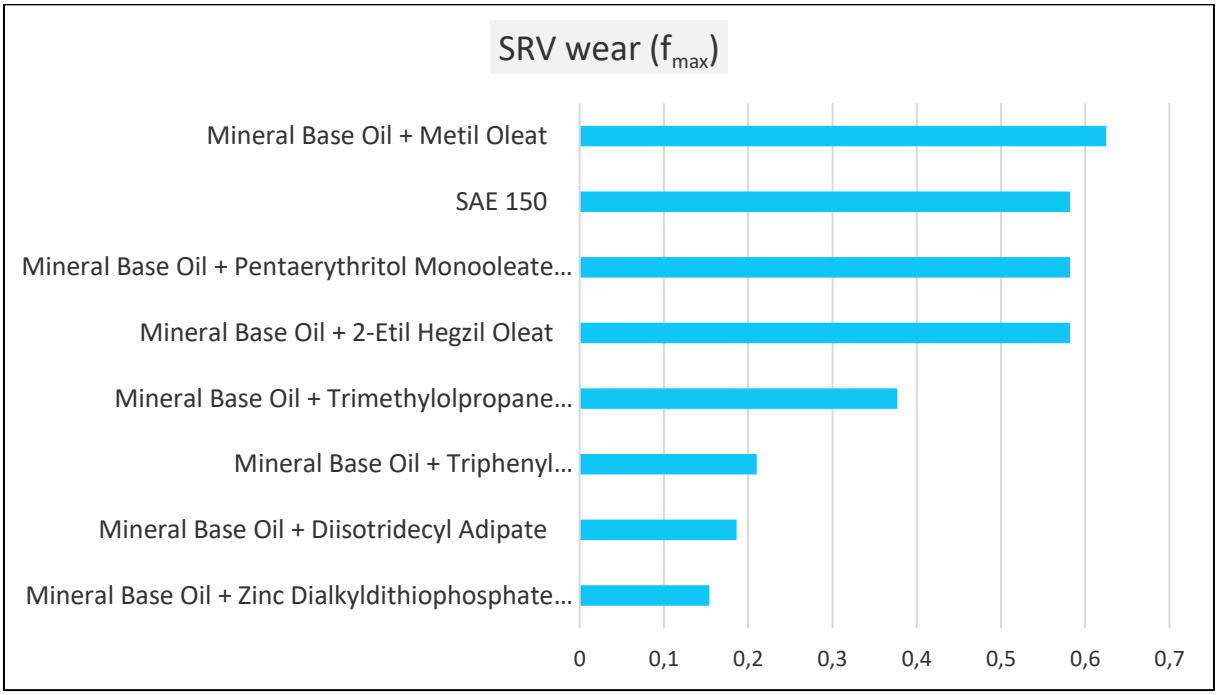


Figure 11. SRV chart of TPPT with ASTM D 6425 method

Table 5. Result table

Product No	Sample Name	SRV wear (f_{max})
*	KV 150 @40˚C Mineral Base Oil	0,582
Pr. 1	Mineral Base Oil + Methyl Oleate	0,625
Pr. 2	Mineral Base Oil + 2-Ethylhexyl Oleate	0,582
Pr. 3	Mineral Base Oil + Pentaerythritol Monooleate (PEMO)	0,582
Pr. 4	Mineral Base Oil +Trimethylolpropane Trioleate (TMPTO)	0,377
Pr. 5	Mineral Base Oil + Diisotridecyl Adipate	0,186
Pr. 6	Mineral Base Oil + Zinc Dialkyldithiophosphate (ZDDP)	0,155
Pr. 7	Mineral Base Oil + Triphenyl Phosphorothionate (TPPT)	0,210

Table 6. Result graphic



The experimental results revealed clear performance differences among the ester-containing formulations.

- Formulations containing simple mono esters showed the weakest anti-wear performance under boundary lubrication conditions.
- The addition of an ester does not automatically guarantee improved friction or wear performance; its effectiveness strongly depends on molecular structure.
- As the ester chain length increases and the molecular architecture becomes more complex, boundary lubrication behavior generally improves.
- Reactive anti-wear additives such as TPPT and ZDDP provided substantially superior protection, outperforming all ester-based formulations.
- In future studies, the wear scars will be further examined using a 3D optical microscope to quantitatively assess wear diameter, depth, and overall surface topography, enabling a more comprehensive correlation between ester structure and wear behavior.

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RE -PROCESSING OF MELON BY - PRODUCTS FOR A VARIETY OF VALORIZED PRODUCTS.

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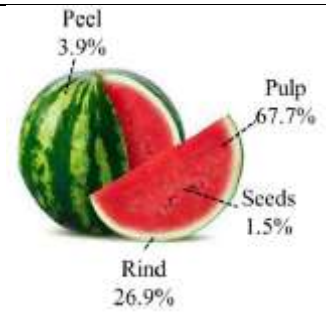
ABSTRACT

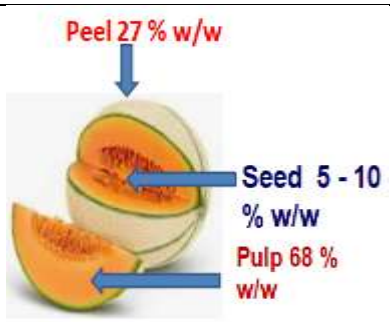
Melons (*Cucumis melo* L.) are a diverse group of fruits belonging to the *Cucurbitaceae* family known for their juicy flesh, sweet flavor and variety of uses due to their nutritional and bioactive properties. Melon crop wastes and processing residues are estimated at 58% to 62% of the fresh mass, including peel, rind, seed, fibrus strand and leftover pulp / pomace, present numerous opportunities for valorization of theses considered as discardable residues. These contain a wide range of phytochemicals, including carotenoids, polyphenols, tocopherols, vitamins, minerals, and dietary fiber. These compounds also exhibit antioxidant, anticancer, anti-inflammatory, anti-diabetic, antimicrobial and functional food properties. These by-products besides significant nutritional benefits present new market opportunities for the food, bakery and beverages as well as for other industrial, commercial, pharmaceutical, **nutraceutical** and cosmetic industries generating the framework of a circular - bio -economy. India produces about 1.3 to 1.5 million tones. Melons come in various shapes, sizes, and colors, each with its own unique taste and nutritional profile.In this paper, we intend to highlight the significance of watermelon, muskmelon, and pumpkin, emphasizing their nutritional, agricultural, and economic importance. These crops are often underappreciated and underutilized despite their high potential, and our objective is to explore their value, promote their wider use, and encourage further research and development in their cultivation and processing.

Keywords: Melon fruits, Watermelon, Muskmelon, Pumpkin, Wastes and processing residues, Food bakery and dairy products, Bakery Products, Commercial products, Industrial products

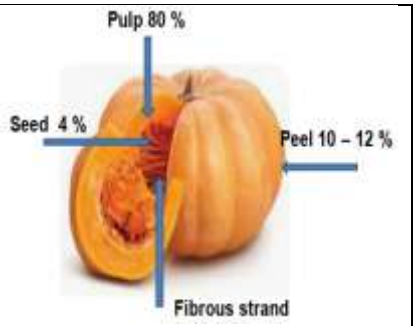
Major Melon Wastes and Processing By – products:



Average proportion of watermelon wastes



Average proportion of muskmelon wastes

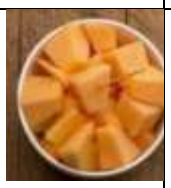


Average proportion of pumpkin wastes

Average Composition of Melon Fruits

Fruit	Peel % of total weight	Rind % of total weight	Seed % of total weight	Pomace (solid residue) % flesh	Edible pulp pulp % of fruit weight	Fibrous strand / funiculi % w/w	Juice % edible flesh
Watermelon	**3 - 9**	**21 - 27**	**1.5**	**5 - 10**	**60 -70**	**--**	**55 – 57 of total weight or 92 % of flesh weight**
Muskmelon	**27**	**-**	**5 -10**	**20 -**	**68**	**--**	**20 of total weight / 90 % of edible flesh**
Pumpkin	**10 - 12%**	**-**	**3.5 – 4.5**	**10 -25**	**79 - 83**	**0.5 – 1.5**	**42 – 56 % of total weight / 87-91% of edible flesh**

Wastes and Processing Residues from Melon Fruits (Edible wastes 30.48%)

 Watermelon Total wastes 33 8 %	 Pulp 66%	 Rind 30%	 Peel 3%	 Seed ! %	 Dehusked seed	 Seed husk
 Muskmelon	 Pulp	----	 Peel	 Seeds	 Dehusked seeds	 Seed husk
 Pumpkin	 Pulp	 Rind	 Peel	 Seed	 Dehusked seeds	 Seed husk

Reprocessed Products from Melon Wastes and Processing Residues

Watermelon

 **Dried peel**	 **Peel powder**	 **Ground peel**	 **Dried rind**	 **Rind powder**
 **Rind extract**	 **Seed**	 **Dehusked seed**	 **Seed powder**	 **Seed Powder**

 Ground seed	 Seed oil	 Seed husk	 Husk churi	 Peel wax
 Pomace / juiced pulp	 Dried pmace	 Pomace Powder	 WM peel marmelade	 Peel curry

Muskmelon

 Peel	 Peel powder	 Seed	 Dehusked seed	 Seed powder / meal
 Ground seed	 Seed oil	 Seed husk	 dried pomace	 ``Dried pulp
 Seed oil	 Seed husk churi	 Candy		

Pumpkin

Pumpkin: Pumpkin by-products comprise various parts, such as seeds, peels, and pulp residues, with their bioactive composition and many potential benefits poorly explored by the food industry. Pumpkin and their by-products contain a wide range of phytochemicals, including carotenoids, polyphenols, tocopherols, vitamins, minerals, and dietary fibers. These

compounds in pumpkin by-products exhibit antioxidant, anticancer, anti-inflammatory, anti-diabetic, and antimicrobial properties

 **Peel**	 **Peel powder**	 **Peel extract**	 **seed**	 **Dehulled seed**
 **Seed husk**	 **Seed powder**	 **Seed oil**(51–62.5%),	 **Pomace**	 **Pomace powder**
 **Seed husk churi**	 **Pumpkin strands**			

Melon seed peeling / de - hulling: The seed kernel from the outer shells / husk is separated by impact - based and wet processing techniques. In mpact-based shelling seeds are collided with a stationary object or rotating impeller where impact force is generated, to crack the shells. In wet dehulling, seeds are water soaked to soften the hulls, followed by mechanical dehulling using using a combination of friction, impact, or pressure. Some of the commercially available machines are shown pictorially below






Utilization of melon wastes and processing by products for food, bakery, pastry, dairy, beverages, commercial, industrial, pharmaceutical and cosmetic products: :

Food products: Extruded snacks (10 – 20%), roasted seeds, chewy snacks food, jams, jelly, pies, dehydrated slices, roasted nuts, puttu (steamed rice cake), snacks (brown rice 90% and seed powder 10 %), chappathi (Indian flat bread). noodles , gluten-free noodles (up to 50 % flour), gluten free pasta (up to 50 % flour), cereal bars, puree, pickle, dosa , halwa , preserve, candy, sweets, confectionery, etc.

Dairy products: Enriched yogurt, cheese, ice cream, curd, flavoured milk, butter cream, dairy beverages, sweets, etc.

Commercial products: Dried peel, paste, peel powder, peel flour, peel extract, dried rind, rind powder, rind flour. flesh , flesh powder, seed, seed powder, seed flour, seed oil, pomace, pomace / leftover pulp / powder, pomace flour, syrup, dietary fiber, animal feed, compost, etc.

Industrial products: Bio ethanol, animal feed , coloring agent in pasta and flour mixes, peel extract, seed oil extract, seed meal, low-cost sorbent to remove dyes, pectin,, edible coating, bio degradable packaging film, nutrient-rich soil amendments, bioplastics, biocomposites, edible coatings, biodegradable foams, activated carbon materials, etc.

Beverages: Soup, syrup, enriched milk, melon seed powder milk, etc.

Bakery products: Bread, bread mix, functional melon waste biscuits, cake, , cookies (10 – 40%), muffins, smoothies, sandwiches, (rind waste up to 20 % cake) , biscuits up to 15 % peel powder in breads, cake, seed flour/ seed residues after oil 10 % in bread, , fortified bread (15 – 25%), seed oil baking and cooking, buns, burgers, waffles, crackers, and doughnuts , etc.

Pharmaceutical products: Bioactive compounds (carotenoids, tocopherols, phytosterols, phenolic compounds, and various vitamins and minerals), . cucurbit in bioactive compound, seed oil, seed extract as anti-inflammatory effects, seed extract as trypsin inhibitor, antioxidant activity.

Cosmeceuticals: seed oil, pulp. face mask, skin care, etc.

Wastes and By products	Utilization
Watermelon Peel	cookies, bread, and muffins, crackers, jam, pickle, smoothies,
Watermelon Peel powder	**Nutritionally enhanced bakery goods, biscuit 50 %, muffins 100 % (biscuit 50 %, muffins 100 %,2024),**
Watermelon rind	Tutti frutti, candy,jam, preserves, fruit butter, chutney, stir fried, pcickle, baked goods like cookies. racker, breads, noodles,
Watermelon rind powder	**Cake 10 – 20 %, biscuit 10 – 20 %, biscuit 50 %, muffins 100 %, cookies 20 - 30%,**
Watermelon seed powder	**Bakery products (10 - 15 % in pasta, 5 – 10% cake)**
Watermelon seed powder	**Bakery products (10 - 15 % in pasta, 5 – 10% in cake and bread)**
Watermelon pomace	Bakery products (cookies and cakes), pasta 15 % w/w, enriched beverages (juices , smoothies,), natural colorant , flavor enhancer, cosmetics,
Watermelon pomace powder:	**Bakery products (10 - 15 % in pasta, 5 – 10% cake). Pickles , Preserves, Curries and Stir-fries, Fruit Butters, pectin, animal feed, biosorbent, cosmetics,**
Muskmelon peel	**Pectin, yogurt,** fruit-flavored milk, 10 – 20 % bakery products,
Muskmelon peel powder	**jams, jellies, and baked goods; biodegradable films, bio coatings, prebiotic supplements; flavor, nutrients, and potentially extending shelf life in dairy products; adding nutritional and functional properties in bakery products,**
Muskmelon seeds	**Fortified breads, cake, melon seed-based beverage, sausages,** cheese or yogurt, **seed meal** bioplastics, biodegradable films, biocomposites, edible coatings, and biodegradable foams, trypsin inhibitor.
Muskmelon seed flour	to enhance the nutritional and functional properties of bread, cake (40%), cookies, muffins, buns, burgers, waffles, crackers, doughnuts, food preservation enhancer, plant-based milk, enzymes. biodegradable film, packaging paper, edible coatings, biodegradable foams. bioethanol, glucose, proteins, enzymes, flavour compounds,
Muskmelon pomace	Enrichment of bakery and pastry goods (bread, cakes, cookies, muffins, crackers, and biscuits, etc) in terms of fiber, texture, flavor, anti oxidants; confectionery products to enhance flavor and improve texture; as a natural texturizer and stabilizer in dairy products; natural colourants; natural flavouring agents; biodegradable films for packaging; dairy products. ice cream, yogurt, paneer, milkshakes; natural glow and skin health as cosmetics;
Muskmelon pomace flour	Flavour and aroma in dairy products - lavored milk, cheese, dairy-based desserts, ice cream, yogurt, milkshakes, paneer ; natural glow and skin health as cosmetics;
Pumpkin peel	Pectin, food products, cosmetics , pharmaceuticals, mayonnaise sause 0.02 – 0.1 %, (गाढ़ा, मलाईदार सॉस)_, natural food colorants , preservatives. Animal feed, snacks, soups, bakeries, and beverages, bio degradable packaging, natural colourants, bio-adsorben, yogurt, 2 – 4 %, biscuit 5 – 15 %, and 10 – 40 %, baked ball 5%, Jam 0.2 – 0.4 %, yogurt 2 – 4 %
Pumpkin peel powder	Natural colorant, dietary fiber, nutrient enrichmer, bread, cakes, and cookies, sensory enhancers, cosmetic skinc are, skin ourishment, cosmetic additives. Biscuit 20% and baked muffins, , yogurt 2 – 4 %, Butter cake and chiffon cake 20%, and chiffon cake; sandwich bread, bread, sweet bread and cookies 10 %, pumpkin powder (10, 20, 30, 40 and 50%) in sandwich bread, sweet bread, butter cake, chiffon cake and cookies. Bread made with 5% pumpkin peel flour,
Pumpkin seed	salads, baked goods, and snacks , Bakery and pastry goods, biscuits, nacks, bread, muffins, crackers, cookies, cakes, cereal bars
Pumpkin seed powder	dressings, soups, and baked goods, snacks, bread, muffins, crackers, cookies, cakes, cereal bars, cream milk, ice cream,
Pumpkin pomace	Jam, jelly, syrup, puree, bread, gluten free noodles and pasts 25%, sausage 30%, cheese, fortified pastry goods , fortified bakery goods, dietary fiber, animal feed
Pumpkin hull flour	bread 2.5% and 5%,
Pumpkin strands	It is part of pomace

GREENHOUSE POTENTIAL OF KONYA PROVINCE AND DIFFERENT GREENHOUSE PRACTICES*

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ABSTRACT

In parallel with the rapid increase in the world population, ensuring healthy and balanced nutrition for humanity has become one of the most critical issues. For a healthy life, it is essential that the foods consumed are grown under safe and hygienic conditions. The Covid-19 pandemic has once again demonstrated to the entire world the importance of agricultural production and the necessity of maintaining agricultural activities under sustainable and healthy conditions. This process has contributed to the expansion of greenhouse production and greenhouse enterprises in the province of Konya. This study was conducted in 2025 to investigate the greenhouse cultivation potential of Konya Province—where greenhouse enterprises have been rapidly established in recent years—and to examine selected greenhouse enterprises recently founded in the region. Konya ranks 29th in Türkiye with a greenhouse area of 1,036 decares. Following the Covid-19 pandemic, greenhouse cultivation areas in Konya increased by 50.58% (TÜİK, 2025). The research findings reveal that the number of greenhouse enterprises in Konya Province has increased rapidly with the Covid-19 pandemic. Considering the agricultural and livestock production potential of the Konya Region, it is evident that this growth will continue. It is recommended that newly established greenhouse enterprises in the region be designed in accordance with the cultivated crop types and local environmental conditions to ensure efficient and sustainable production.

Keywords: Konya, Greenhouse Enterprise, Sustainable Agriculture.

*This study is produced from the master's thesis of Muhammed Işık.

INTRODUCTION

Greenhouse structures play a critical role in modern agricultural production by enabling the cultivation of crops under controlled environmental conditions during periods when natural climatic factors are unsuitable for plant growth. Defined as steel- or wood-framed structures covered with glass or plastic, greenhouses provide all environmental parameters required for plant development regardless of external conditions, thereby allowing continuous production for seedling cultivation, crop production, research, and demonstration purposes (Demir, 2001; Baytorun, 2016).

Greenhouse cultivation significantly contributes to the agricultural economy in Türkiye by increasing productivity per unit area, reducing unemployment rates, improving rural welfare, and ensuring the efficient use of limited agricultural land. Greenhouse enterprises not only offer year-round employment opportunities for farmers but also support the emergence of new industrial sectors involved in the production of greenhouse equipment. Compared to open-field agriculture, greenhouses yield two to three times higher output, shorten growing periods, enable multiple harvests from the same plot within a year, and ensure stable labor distribution in small-scale agricultural operations (Anonymous, 2018a).

Globally, approximately 800,000 hectares are devoted to greenhouse cultivation, with Mediterranean countries accounting for a substantial share of this area. Of these protected cultivation areas, 85% consist of plastic-covered greenhouses and 15% of glass-covered structures (Silleli et al., 2020). Türkiye ranks fourth globally and second in Europe after Spain in terms of greenhouse production area (Ministry of Agriculture and Forestry, 2019). The country's total greenhouse area amounts to 776,110 decares, comprising 58.4% plastic greenhouses, 7.21% glass greenhouses, 21.04% low tunnels, and 13.40% high tunnels (TÜİK, 2024).

Rapid population growth in Türkiye, advancements in export markets, increasing awareness of healthy nutrition, and the recognized importance of fruit and vegetable consumption have all accelerated innovation in agriculture. This surge in consumer demand has led to a rapid expansion of greenhouse cultivation alongside traditional open-field production, resulting in the establishment of numerous new greenhouse enterprises (Saltuk, 2014).

In recent years, the COVID-19 pandemic has caused significant global disruption, resulting in loss of life, economic instability, and sector-wide crises. At the same time, the pandemic highlighted the critical importance of food security and balanced nutrition. Consequently, governmental and societal support for agriculture has intensified, accompanied by a pronounced global increase in greenhouse construction. Greenhouse cultivation has expanded even in regions previously considered unsuitable. Thus, evaluating the structural characteristics, operational capacities, and development potential of greenhouses in regions with extensive agricultural land such as Konya Province has become increasingly important.

Konya, which ranks 29th among Turkish provinces in greenhouse cultivation area, has experienced significant growth in greenhouse activities, particularly following the COVID-19 pandemic. This study aims to assess the greenhouse cultivation potential of Konya Province and to examine the structural and operational characteristics of representative greenhouse enterprises established in the region.

GREENHOUSE CULTIVATION IN THE WORLD

Plant production is carried out worldwide using two primary methods: open-field cultivation and protected cultivation. Activities conducted in protected areas have given rise to greenhouse cultivation. The historical origins of greenhouse cultivation date back to the Roman Empire,

with the earliest documented examples appearing around 30 A.D. during the reign of Emperor Tiberius (Anonymous, 2015). In historical practice, instead of glass or plastic coverings commonly used today, pits excavated on mountain slopes facing south were covered with thin cloth polished with oil or beeswax, or with semi-transparent mica sheets, known as *specularium*. The main motivation behind this practice was Emperor Tiberius's desire to consume cucumbers out of season (Üçışık Erbilen & Şahin, 2011). In 1599, the first greenhouse was constructed in Leiden, the Netherlands, for the purpose of cultivating tropical medicinal plants (Anonymous, 2007a; 2010). In this greenhouse, *Tamarindus indica*, a species of the Fabaceae family native to Egypt and India, was cultivated (Üçışık Erbilen & Şahin, 2011).

Globally, greenhouse cultivation began in Italy during the Roman period, and structures built up to the 16th and 17th centuries are considered the earliest examples of greenhouse agriculture. Following the Industrial Revolution, greenhouse construction in the United States and Europe accelerated rapidly after the First World War. Today, it is known that greenhouses have a wide global distribution, characterized by diverse ecological conditions and highly varied, continuously developing greenhouse technologies (Yağanoğlu, 2014).

Greenhouse cultivation worldwide can be classified into three categories based on climatic zones: cool climate, temperate climate, and countries with dual climatic characteristics. Countries within the cool climate zone include the Netherlands, the United Kingdom, Denmark, Germany, Romania, Bulgaria, and Russia. Countries in the temperate climate zone include Türkiye, Spain, France, Japan, Italy, Greece, and Israel. The United States is the leading country representing the dual-climate category, with the common feature of cultivating in both glass and plastic greenhouses. Among the countries in the cool climate zone, the Netherlands stands out with 10,000 hectares of glass-covered greenhouse area and advanced cultivation techniques (Anonymous, 2022a).

Although the first greenhouses were established in Europe, greenhouses built for commercial production emerged in the United States during the 18th century (Bayraktar, 1964). The first greenhouse in the United States was constructed in 1737 by a wealthy merchant in Boston. Beginning in 1825, protected cultivation activities developed rapidly, and today they are practiced throughout nearly all regions of the country, from Alaska to California (Üçışık Erbilen & Şahin, 2011).

Greenhouse cultivation expanded significantly beginning in the 18th century. In the Netherlands, greenhouses were initially used to protect endemic plants brought from tropical climates and to overwinter them. Later, greenhouses were used to cultivate fruits, vegetables, flowers, and herbs that could not grow and develop during cold seasons.

A major breakthrough in greenhouse cultivation occurred in the 1960s when plastic coverings were first introduced in Japan (Jensen & Malter, 1995). Plastic-covered greenhouses gradually replaced glass-covered ones due to their lower cost and spread from North America to Europe. Today, protected cultivation is practiced across wide areas in many countries, including Canada, Romania, Spain, and Japan. The regions where greenhouse cultivation is most successfully implemented lie between 30° and 40° north and south latitudes and in Mediterranean Basin countries (China, South Korea, Spain, Japan, Türkiye, India, Italy, Mexico, the Netherlands, France, and the United States). Until the mid-20th century, greenhouses were classified according to the types of plants cultivated inside them (e.g., cucumber, tomato, carnation, flower, and pot-plant greenhouses). Today, greenhouse prevalence and technology are continually increasing, and greenhouses are constructed in various designs (Figures 1 and 2). Greenhouses constructed under contemporary conditions can

be used to cultivate different plant species thanks to advanced control systems (Baytorun, 2016).

GREENHOUSE CULTİVATİON İN TÜRKİYE

Türkiye holds a significant position in global vegetable and fruit production due to its favorable ecological characteristics. However, modern greenhouse production in the country began in the 1940s along the Mediterranean coastal belt, and has shown marked development since the 1970s. Although greenhouse cultivation can be practiced in various regions of the country, the availability of suitable environmental conditions, economic factors, transportation and marketing possibilities are determinants that either limit or enhance the prevalence of greenhouse enterprises. In addition, in regions that are less suitable for greenhouse cultivation but are located close to major consumption centers, the reduction in transportation costs may outweigh the increase in heating expenses, making greenhouse establishment a viable option. In this context, technical measures such as utilizing solar energy to reduce heating costs and benefiting from geothermal resources (hot water, boiling water, and steam) constitute important strategies that could significantly contribute to the expansion of greenhouse enterprise areas in Türkiye (Anonymous, 2023).

The plastic greenhouse area in Türkiye is 452,907 decares. Antalya, the most important center of greenhouse cultivation in the country, possesses 245,109 decares of plastic greenhouse area. Following Antalya, Mersin ranks second with 99,633 decares. The plastic greenhouse area in Konya is 520 decares. With technological advancements, increasing emphasis has been placed on modern and well-equipped greenhouse structures. Among the commonly used greenhouse types in Türkiye, steel-frame plastic-covered greenhouses are predominantly preferred (Figure 3). Due to developments in plastic covering materials, the use of glass-covered greenhouses has decreased compared to past decades, owing to cost and service-life considerations. Because of the high rate and duration of sunshine in Antalya Province, 79% of all glass-covered greenhouses in Türkiye are located in this region (TÜİK, 2024) (Figure 4).

Protected cultivation practices in Türkiye began in the 1940s with the establishment of glass-covered greenhouses in Antalya. Between 1940 and 1960, greenhouse development remained limited (Tüzel et al., 2005). The most significant period of advancement in greenhouse cultivation began in the 1970s, primarily due to the replacement of glass covering with polyethylene (PE) material, which is lighter, more economical, and easier to apply (Öneş, 1986; Çolak, 2002). There were notable increases in greenhouse areas between 1975 and 1985, and a growth rate of 64.5% was recorded between 1990 and 1997 (Tüzel & Eltez, 1997; Sevgican, 2000). Although a short-term decline occurred in 2001 as a result of the economic crisis, the upward trend in greenhouse area has continued in subsequent years.

Cold winter conditions adversely affect field cultivation under current climatic circumstances, thereby increasing the importance of greenhouse production. The total protected cultivation area in Türkiye increased from 660,265 decares in 2015 to 776,110 decares in 2024. During this period, the glass greenhouse area decreased from 79,977 decares to 55,949 decares, while the plastic greenhouse area expanded from 306,074 decares to 452,907 decares. Low-tunnel and high-tunnel areas were recorded as 161,541 decares and 112,674 decares in 2015, and 163,276 decares and 103,978 decares, respectively, in 2024. Thus, as of 2024, the total greenhouse area in Türkiye has reached 776,110 decares (TÜİK, 2024) (Table 1.1).

Table 1.1. Annual Change in Covered (Protected) Agricultural Areas in Turkey (TÜİK, 2024)

Year	Total (da)	Glass Greenhouse (da)	Plastic Greenhouse (da)	High Tunnel (da)	Low Tunnel (da)
2015	660 265	79 977	306 074	112 674	161 541
2016	691 724	80 137	328 745	112 974	169 867
2017	752 168	85 749	355 121	119 899	191 399
2018	772 091	78 110	368 527	114 232	211 222
2019	789 604	75 495	378 670	111 038	224 400
2020	805 159	80 779	401 795	104 258	218 326
2021	854 600	76 213	464 973	100 756	212 657
2022	810 881	59 633	471 284	110 426	169 538
2023	764 206	55 312	448 510	117 743	142 642
2024	776 110	55 949	452 907	103 978	163 276

The Mediterranean Region, which has the most suitable climatic conditions in Turkey, possesses the highest proportion of protected cultivation areas, accounting for 84%. It is followed by the Aegean Region (9.4%), the Black Sea Region (4.8%), and the Marmara Region (1.7%). Within the Mediterranean Region, Antalya ranks first with 37.90% of protected cultivation areas, followed by Mersin with 40.84%, while Adana ranks third with 22.81% and 16.85% (Table 1.2).

Table 1.2. Selected Provinces in Turkey with Protected Cultivation Areas (Ministry of Agriculture and Forestry, 2024)

Province	Glass Greenhouse Area (da)	Plastic Greenhouse Area (da)	Total Greenhouse Area (da)	Low Tunnel Area (da)	High Tunnel Area (da)	Total Protected Cultivation Area (da)
Antalya	44,336	245,109	289,445	12,113	15,399	316,957
Mersin	5,568	99,633	105,201	35,168	36,683	177,052
Adana	2	7,156	7,158	105,767	17,838	130,763
Eskişehir	5	5,625	5,630	–	365	5,995
Konya	41	520	561	51	424	1,036
Ankara	1	419	420	8	128	556
Karaman	9	252	261	–	–	261
Aksaray	–	138	138	35	48	221
Kayseri	23	62	85	–	17	102
Niğde	–	42	42	–	–	42
Turkey	**55,949**	**452,907**	**508,856**	**163,276**	**103,978**	**776,110**

GREENHOUSE CULTİVATİON İN KONYA

In recent years, a remarkable increase has been observed in protected cultivation areas in Konya, particularly following the Covid-19 pandemic. Greenhouse enterprises utilizing geothermal heating have become increasingly common in the districts of Ilgın, Hüyük, and Karatay where geothermal resources are concentrated as well as in Tuzlukçu, Seydişehir, and Cihanbeyli, where new geothermal sources have recently been identified. The use of geothermal

water and the efficient utilization of waste heat derived from these resources enable the establishment of protected cultivation facilities and contribute to the use of low-cost energy alternatives. Furthermore, the extensive agricultural land available in Konya positively supports this expansion. Consequently, the number of technologically advanced greenhouses with large production areas and geothermal-based heating systems has increased significantly in the region.

REPRESENTATİVE GREENHOUSE EXAMPLES İN KONYA

Within the scope of this study, five greenhouse enterprises established in recent years in the Konya Region selected for their high level of technological integration and representativeness were examined as case examples.

BUTTERFLY VALLEY GREENHOUSE

One of the world's most distinctive exhibition-type greenhouses is the Butterfly Valley located in Konya Province. Designed as a modern exhibition facility built in the form of a butterfly when viewed from above, this greenhouse was established for the display of tropical butterfly species as well as selected plant varieties. Butterfly Valley is situated within a valley surrounded by tulip gardens and hosts a wide range of recreational and educational activities (TÜİK, 2021e) (Figure 1).



Figure 1. Perspective View of the Butterfly Valley Greenhouse, Konya, Türkiye (Anonymous, 2025a)

NUMBER 2 GREENHOUSE ENTERPRİSE

Located in the Çumra district of Konya, the greenhouse enterprise owned by Konya Şeker Ltd. Şti. is established on a total area of 60,000 m², of which 38,500 m² consists of fully controlled, steel-constructed Venlo-type glass greenhouses where tomato cultivation is carried out. The tomatoes are grown using soilless culture techniques in gutter systems. Steam generated during the processing of sugar beet at the Konya Sugar Factory is utilized for heating the greenhouses.

The greenhouse, designed as a narrow-span Venlo type, has a sidewall height of 6.00 m. In addition to tomato production, crops such as cucumber, banana, cocoa, date palm, and raspberry species that cannot naturally be grown under Konya's climatic conditions are cultivated in these greenhouses. Moreover, banana cultivation is carried out in plastic greenhouses within the enterprise, and tropical fish production is also conducted in plastic greenhouse structures.

The enterprise employs systems that ensure water and energy savings, enabling fully controlled production conditions and efficient use of water and fertilizers.



Figure 2. Perspective View of Greenhouse Enterprise No. 1, Çumra, Konya, Türkiye (Anonymous, 2025b)



Figure 2. Interior View of the Greenhouses in Greenhouse Enterprise No. 1 (Anonymous, 2025c)

NUMBER 2 GREENHOUSE ENTERPRİSE

The greenhouse enterprise located in the Cihanbeyli district of Konya is established on an area of 7,072 hectares, with 110,000 m² allocated to tomato cultivation in steel-constructed plastic greenhouses designed with a gothic roof structure. In Greenhouse Enterprise No. 2, geothermal hot water is used for heating, and as shown in Figure 3, soilless cultivation techniques are applied. The enterprise plans to carry out production using a modern, fully automated, soilless greenhouse system.



Figure 3. Perspective View of Greenhouse Enterprise No. 2, Cihanbeyli, Konya, Türkiye (Anonymous, 2025d)



Figure 4. Interior View of the Greenhouses in Greenhouse Enterprise No. 2 (Anonymous, 2025e)

NUMBER 3 GREENHOUSE ENTERPRİSE

The greenhouse enterprise established in the Meram district of Konya operates on an area of 3,250 m², where seedling production is carried out in a steel-constructed greenhouse covered with polycarbonate panels. The facility has an annual production capacity of 12 million seedlings. It produces healthy and high-yield vegetable and ornamental plant seedlings to support growers in Konya in obtaining higher-quality products.

Greenhouse Enterprise No. 3 was established with the financial support of the Konya Plain Project (KOP) Regional Development Administration, Meram Municipality, Karatay Chamber of Agriculture, and the Central Konya Vegetable Producers Union.



Figure 5. Perspective View of Greenhouse Enterprise No. 3 (Anonymous, 2025f)



Şekil 6 **.** 3 Nolu Seracılık İşletmesinde Bulunan Seraların İçerisinden Görünüm (Anonim, 2025g)

NUMBER 4 GREENHOUSE ENTERPRİSE

The greenhouse enterprise established in the Tuzlukçu district of Konya Province covers an area of 100,000 m², where year-round production is carried out in steel-construction greenhouses. In these facilities, tomato cultivation is conducted using soilless farming techniques. To ensure optimal greenhouse microclimate conditions in the Konya region, the enterprise utilizes seven geothermal sources located within the area, while also incorporating renewable energy systems (such as solar energy) to support heating.



Figure 7. Perspective View of the 4th Greenhouse Enterprise (Anonymous, 2025h)



Figure 7. Interior View of the Greenhouses in the 4th Greenhouse Enterprise (Anonymous, 2025ı)

CONCLUSION

The findings of this study demonstrate that the rapid increase in the global population, coupled with the impacts of the Covid-19 pandemic, has significantly heightened the need for reliable, balanced, and healthy nutrition. Achieving this goal depends fundamentally on the use of high-quality seeds developed under controlled conditions and the cultivation of crops in environments that ensure plant health and optimal growth. Greenhouse cultivation has therefore emerged as a critical production system, as it enables the controlled manipulation of environmental factors, the cultivation of species with diverse ecological requirements, and the consistent production of high-quality agricultural outputs.

Greenhouses also provide unique opportunities for biodiversity conservation and exhibition by allowing the cultivation of plants and organisms originating from various ecological zones. The ability to produce year-round not only accelerates plant breeding programs but also facilitates multiple cropping cycles, thereby increasing overall productivity. In this regard, Konya Province possesses considerable potential for greenhouse-based agriculture, as evidenced by the rapid establishment of technologically advanced greenhouse enterprises supported by abundant geothermal resources and expansive agricultural lands.

For the sustainable expansion of greenhouse cultivation in the region, it is essential that future greenhouse structures be designed with close attention to local climatic and environmental conditions as well as the technical requirements of modern controlled-environment agriculture. Based on the analysis conducted, it is recommended that greenhouse enterprises—and their associated technical and auxiliary units—be systematically evaluated, that operational constraints be identified through comprehensive field studies, and that targeted and region-specific solutions be developed to improve efficiency, sustainability, and technological integration.

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CRISPR-Cas9 İLE BİTKİ ISLAHINDA HEDEFE YÖNELİK GEN DÜZENLEME

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Özet

Artan dünya nüfusu, iklim değişikliği ve doğal kaynakların sınırlılığı, bitkisel üretimde daha verimli, kaliteli ve stres koşullarına dayanıklı çeşitlerin geliştirilmesini zorunlu kılmaktadır. Geleneksel bitki ıslahı yöntemleri uzun zaman gerektirmesi ve çevresel faktörlerden yoğun biçimde etkilenmesi nedeniyle bu ihtiyaçlara sınırlı hızda cevap verebilmektedir. Moleküler biyoloji ve biyoteknolojide yaşanan gelişmeler, bitki genomunun doğrudan ve hedefe yönelik olarak düzenlenmesine olanak sağlayan yeni yaklaşımların ortaya çıkmasına zemin hazırlamıştır. Bu yaklaşımlar arasında CRISPR-Cas9 genom düzenleme teknolojisi, yüksek özgüllüğü, görece düşük maliyeti ve uygulama kolaylığı sayesinde bitki ıslahında devrim niteliğinde bir araç olarak öne çıkmaktadır. Bu derlemede CRISPR-Cas9 teknolojisinin temel çalışma prensibi, bitki ıslahında kullanım alanları, sağladığı avantajlar, karşılaşılan sınırlılıklar ve gelecekteki potansiyeli sade ve bilimsel bir çerçevede ele alınmıştır.

Anahtar Kelimeler: CRISPR-Cas9, genom düzenleme, bitki ıslahı, biyoteknoloji

TARGETED GENE EDITING IN PLANT BREEDING USING CRISPR–Cas9

Abstract

The increasing global population, climate change, and the limited availability of natural resources necessitate the development of crop varieties that are more productive, high-quality, and resilient to stress conditions. Conventional plant breeding methods often require long periods of time and are strongly influenced by environmental factors, which limits their ability to respond rapidly to these demands. Advances in molecular biology and biotechnology have paved the way for novel approaches that enable direct and targeted modification of plant genomes. Among these approaches, CRISPR–Cas9 genome editing technology has emerged as a revolutionary tool in plant breeding due to its high specificity, relatively low cost, and ease of application. This review addresses the basic working principle of CRISPR–Cas9 technology, its applications in plant breeding, the advantages it offers, the limitations encountered, and its future potential within a clear and scientific framework.

Keywords: CRISPR-Cas9, genome editing, plant breeding, biotechnology

1. Giriş

Bitki ıslahı, tarımsal üretimin sürdürülebilirliği ve insanlığın artan gıda ihtiyacının karşılanmasında tarih boyunca temel bir rol üstlenmiştir. Tarımın ilk dönemlerinden itibaren insanlar, yüksek verimli, çevre koşullarına daha iyi uyum sağlayabilen ve tüketim açısından tercih edilen bitkileri seçerek üretimde kullanmıştır. Seleksiyon, melezleme ve adaptasyona dayalı klasik bitki ıslahı yöntemleri sayesinde günümüzde yaygın olarak yetiştirilen birçok tarım bitkisi geliştirilmiştir. Ancak bu yöntemler, büyük ölçüde uzun zaman gerektirmesi ve çevresel faktörlerin etkisine açık olması nedeniyle modern tarımın artan taleplerini karşılamada yetersiz kalabilmektedir (Doğan, 2024).

Günümüzde dünya nüfusundaki hızlı artış, iklim değişikliğine bağlı olarak ortaya çıkan kuraklık, sıcaklık stresi ve tuzluluk gibi abiyotik stresler ile hastalık ve zararlı baskısındaki artış, bitkisel üretimi doğrudan tehdit etmektedir. Bununla birlikte su ve toprak gibi doğal kaynakların giderek azalması ve tüketicilerin ürün kalitesi, besin değeri ve gıda güvenliği konularındaki beklentilerinin yükselmesi, bitki ıslahında daha hızlı, etkin ve hassas yaklaşımların geliştirilmesini zorunlu hale getirmiştir. Bu koşullar altında, klasik ıslah yöntemlerinin moleküler ve biyoteknolojik yaklaşımlarla desteklenmesi kaçınılmaz olmuştur.

Moleküler markör teknolojileri, genetik haritalama çalışmaları ve yeni nesil genom dizileme yöntemleri, bitkilerde verim, kalite ve stres toleransı gibi özelliklerin genetik temellerinin daha ayrıntılı bir şekilde ortaya konmasını sağlamıştır. Bu gelişmeler, istenilen özelliklerden sorumlu genlerin veya gen bölgelerinin tanımlanmasına olanak tanımış ve bitki ıslahında daha hedefe yönelik stratejilerin uygulanmasının önünü açmıştır. Bu bağlamda, genetik değişikliklerin rastgele değil, belirli hedefler doğrultusunda gerçekleştirilmesini sağlayan genom düzenleme teknolojileri, modern bitki ıslahının önemli araçları haline gelmiştir (Yücel, 2023).

Zinc parmak nükleazları (ZFN) ve Transkripsiyon Aktivatör Benzeri Efektör Nükleazlar (TALEN) gibi erken dönem genom düzenleme sistemleri, hedef DNA bölgelerinde kontrollü değişiklikler yapılabileceğini göstermesi açısından önemli birer kilometre taşı olmuştur. Ancak bu sistemlerin tasarım ve uygulama süreçlerinin karmaşık olması, yüksek maliyet gerektirmesi ve her hedef gen için ayrı protein mühendisliği ihtiyacı doğurması, kullanım alanlarını sınırlamıştır (Tufan, 2019).

Bu sınırlılıkların aşılmasında CRISPR-Cas9 genom düzenleme sistemi önemli bir dönüm noktası olmuştur. Basit tasarımı, kolay uygulanabilirliği ve yüksek hedef özgüllüğü sayesinde CRISPR-Cas9, bitki genomunda istenilen bölgelerin hızlı ve etkin bir şekilde düzenlenmesine olanak tanımaktadır. Ayrıca aynı anda birden fazla genin düzenlenebilmesi, bu teknolojiyi özellikle kompleks özelliklerin kontrol edildiği bitki ıslahı çalışmalarında son derece cazip hale getirmiştir. Bu özellikleriyle CRISPR-Cas9, klasik ve moleküler ıslah yaklaşımlarını tamamlayan, modern bitki ıslahında yeni bir dönemin kapılarını aralayan güçlü bir araç olarak öne çıkmaktadır (Akbudak ve Kontbay, 2017).

2. CRISPR-Cas9 Teknolojisi

CRISPR-Cas9 teknolojisi, bakterilerin ve arkelerin virüs kaynaklı genetik saldırılara karşı geliştirdiği doğal bir bağışıklık sisteminden uyarlanmıştır. Bu sistem, mikroorganizmaların daha önce karşılaştıkları virüslerin genetik bilgilerini tanımasını ve bu yabancı DNA'yı etkisiz hale getirmesini sağlamaktadır. Bitki biyoteknolojisinde kullanılan CRISPR-Cas9 sistemi ise bu doğal mekanizmanın kontrollü ve hedefe yönelik biçimde yeniden tasarlanmış bir versiyonudur. CRISPR-Cas9 sistemi temel olarak iki ana bileşenden oluşmaktadır: kılavuz RNA (single guide RNA; sgRNA) ve Cas9 endonükleaz enzimi. Kılavuz RNA, genom üzerinde düzenlenmesi hedeflenen DNA dizisine tamamlayıcı olacak şekilde tasarlanır. Bu RNA

molekülü, Cas9 enzimine hedef DNA bölgesini adeta bir "adres" gibi tanımlar. Cas9 enzimi ise kılavuz RNA tarafından belirlenen bu hedef bölgeye yönlendirilerek DNA üzerinde kesim işlemini gerçekleştirir (Samanta ve Gayen, 2016). Hedef DNA dizisinin tanınabilmesi için, kesim yapılacak bölgenin yakınında PAM (Protospacer Adjacent Motif) olarak adlandırılan kısa bir nükleotid dizisinin bulunması gerekmektedir. PAM dizisi, Cas9 enziminin DNA'yı tanıması ve bağlanması için zorunlu bir unsurdur. Bu özellik, CRISPR-Cas9 sisteminin genom üzerinde rastgele değil, yalnızca belirli ve tanımlı bölgelerde etkili olmasını sağlamaktadır. Cas9 enzimi, hedef DNA bölgesinde çift zincirli bir kırık (double-strand break) oluşturarak genom düzenleme sürecini başlatır. Bu kırık, hücre için ciddi bir hasar niteliğindedir ve bitki hücresi bu hasarı onarmak üzere kendi doğal DNA tamir mekanizmalarını devreye sokar. CRISPR-Cas9 teknolojisinin etkinliği, büyük ölçüde bu tamir mekanizmalarının sonuçlarına dayanmaktadır. Bitki hücrelerinde en sık devreye giren DNA onarım yolu, non-homologous end joining (NHEJ) mekanizmasıdır. Bu yol, kırık DNA uçlarını hızlı bir şekilde birleştirir; ancak süreç sırasında çoğunlukla küçük ekleme (insertiyon) veya silinmeler (delesyon) meydana gelir. Bu tür değişiklikler, hedef genin okuma çerçevesini bozarak genin işlevini kaybetmesine yol açabilir. Bu nedenle NHEJ mekanizması, özellikle bir genin etkisiz hale getirilmesinin amaçlandığı çalışmalarda yaygın olarak kullanılmaktadır. Alternatif bir onarım yolu olan homologous recombination (HR) mekanizması ise daha kontrollü ve hassas genetik değişikliklere olanak tanımaktadır. Bu yaklaşımda, hücreye dışarıdan verilen bir DNA şablonu kullanılarak, hedef bölgede istenilen genetik dizinin eklenmesi veya belirli nükleotid değişikliklerinin yapılması mümkün olmaktadır. Ancak bitki hücrelerinde HR mekanizmasının etkinliği genellikle NHEJ'ye kıyasla daha düşüktür ve uygulama açısından daha fazla teknik zorluk içermektedir (Liu ve ark. 2017). Sonuç olarak CRISPR-Cas9 teknolojisi, hedef DNA dizilerinde kontrollü çift zincirli kırıklar oluşturarak, bitkilerin kendi onarım mekanizmalarından yararlanılmasını esas alan bir genom düzenleme yaklaşımıdır. Bu sistem, genlerin işlevinin ortadan kaldırılması, düzenlenmesi veya yeni genetik özelliklerin kazandırılması gibi farklı amaçlarla kullanılabilmekte; bu yönüyle modern bitki ıslahında son derece esnek ve güçlü bir araç olarak değerlendirilmektedir (Shan ve ark. 2020).

3. Bitki Islahında Hedefe Yönelik Gen Düzenleme

CRISPR-Cas9 teknolojisinin bitki ıslahındaki en önemli katkısı, genetik değişikliklerin rastlantısal değil, önceden belirlenmiş hedef genler üzerinden gerçekleştirilebilmesidir. Bu yaklaşım, klasik mutasyon ıslahı yöntemlerinde görülen istenmeyen yan etkilerin büyük ölçüde önüne geçmektedir.

Hedefe yönelik gen düzenleme sayesinde: Verimle ilişkili genler doğrudan modifiye edilebilmekte, hastalık ve zararlılara duyarlılığı artıran genler etkisiz hale getirilebilmekte, abiyotik stres toleransında rol oynayan genlerin ekspresyonu düzenlenebilmektedir. Bu durum, ıslah sürecini hem hızlandırmakta hem de elde edilen genotiplerin daha öngörülebilir özellikler sergilemesini sağlamaktadır (Saini ve ark., 2023).

4. Verim ve Kalite Özelliklerinin İyileştirilmesi

Verim ve kalite, bitki ıslahının temel hedefleri arasında yer almaktadır. CRISPR-Cas9 teknolojisi, fotosentez verimliliği, tane iriliği, biyokütle üretimi ve besin içeriği gibi özelliklerin genetik kontrolünde görev alan genlerin düzenlenmesine olanak tanımaktadır. Özellikle tek veya az sayıda gen tarafından kontrol edilen kalite özelliklerinde, bu teknoloji oldukça etkili sonuçlar sunmaktadır. Besin değeri artırılmış bitkiler, düşük glütenli veya alerjen içeriği azaltılmış ürünler ve raf ömrü uzatılmış meyve-sebzeler, CRISPR-Cas9 destekli ıslah çalışmalarının dikkat çeken çıktıları arasında yer almaktadır. Bu sayede hem üretici hem de

tüketici beklentilerine daha iyi cevap veren çeşitlerin geliştirilmesi mümkün olmaktadır (Jung ve ark. 2018).

5. Biyotik ve Abiyotik Streslere Dayanıklılık

Tarımda verim kayıplarının önemli bir kısmı hastalıklar, zararlılar ve çevresel stres faktörlerinden kaynaklanmaktadır. CRISPR-Cas9 teknolojisi, bu streslere duyarlılığı artıran genlerin devre dışı bırakılması veya toleransla ilişkili genlerin düzenlenmesi yoluyla dayanıklı bitkilerin geliştirilmesine katkı sağlamaktadır. Kuraklık, tuzluluk ve yüksek sıcaklık gibi abiyotik stresler, özellikle iklim değişikliği bağlamında daha büyük bir tehdit oluşturmaktadır. Hedefe yönelik gen düzenleme, bitkilerin bu stres koşullarına adaptasyon kapasitesini artırarak sürdürülebilir tarıma önemli katkılar sunmaktadır (Hua ve ark. 2019).

6. CRISPR-Cas9 Teknolojisinin Avantajları

CRISPR-Cas9'un bitki ıslahında yaygınlaşmasının temel nedenleri arasında:

- ✓ Yüksek özgüllük ve hassasiyet,
- ✓ Görece düşük maliyet,
- ✓ Kısa sürede sonuç alınabilmesi,
- ✓ Aynı anda birden fazla genin düzenlenebilmesi,
- ✓ Transgenik olmayan ürünlerin geliştirilebilmesi yer almaktadır.

Bu avantajlar, teknolojinin hem araştırma hem de uygulama aşamalarında tercih edilmesini sağlamaktadır (Chen ve ark. 2019).

7. Dezavantajları ve Etik Boyutu

Her ne kadar CRISPR-Cas9 teknolojisi önemli avantajlar sunsa da bazı sınırlılıklar da mevcuttur. Hedef dışı etkiler, her ne kadar son yıllarda geliştirilen tasarım araçlarıyla azaltılmış olsa da hâlen dikkat edilmesi gereken bir konudur. Ayrıca bitkilerde gen transferi ve rejenerasyon süreçleri, tür ve genotipe bağlı olarak zorluklar içerebilmektedir. Regülasyon açısından ise CRISPR-Cas9 ile elde edilen ürünlerin genetiği değiştirilmiş organizmalar kapsamında değerlendirilip değerlendirilmeyeceği, ülkeden ülkeye farklılık göstermektedir. Bu durum, teknolojinin ticarileşme sürecini doğrudan etkilemektedir. CRISPR-Cas9 teknolojisinin, yeni nesil genom düzenleme sistemleriyle birlikte daha da gelişmesi beklenmektedir. Baz düzenleme ve prime editing gibi yaklaşımlar, daha hassas ve kontrollü genetik değişikliklere olanak tanımaktadır. Bu gelişmeler, bitki ıslahında hedefe yönelik gen düzenlemenin kapsamını daha da genişletecektir (Louwaars ve Jochemsen 2021). Gelecekte CRISPR-Cas9'un; dijital tarım, fenotipleme sistemleri ve yapay zekâ destekli ıslah programlarıyla entegre edilmesi, bitki ıslahında yeni bir paradigmanın oluşmasına zemin hazırlayacaktır (Zhao ve Wolt 2017).

8. Sonuç

CRISPR-Cas9 genom düzenleme teknolojisi, bitki ıslahında hedefe yönelik genetik değişikliklerin yapılmasını mümkün kılarak, klasik ıslah yaklaşımlarının hem hız hem de hassasiyet açısından önemli ölçüde ötesine geçilmesini sağlamıştır. Belirli genlerin doğrudan düzenlenebilmesi, ıslah sürecinde uzun yıllar gerektiren seleksiyon ve geriye melezleme aşamalarını büyük ölçüde kısaltmakta ve elde edilen sonuçların daha öngörülebilir olmasına katkı sunmaktadır. Bu teknoloji sayesinde verim, ürün kalitesi ve besin değeri gibi doğrudan ekonomik öneme sahip özelliklerin yanı sıra, kuraklık, tuzluluk ve yüksek sıcaklık gibi abiyotik

stresler ile hastalık ve zararlılara karşı dayanıklılık gibi özellikler daha etkin bir biçimde geliştirilebilmektedir. Özellikle tek ya da sınırlı sayıda gen tarafından kontrol edilen özelliklerde CRISPR-Cas9'un sunduğu hassas düzenleme imkânı, bitki ıslahında önemli bir avantaj oluşturmaktadır. Ayrıca aynı anda birden fazla genin düzenlenebilmesi, kompleks özelliklerin iyileştirilmesine yönelik yeni olanaklar sunmaktadır. Bununla birlikte, hedef dışı etkiler, bitkiye gen aktarımı ve rejenerasyon süreçlerindeki teknik sınırlılıklar ile düzenleyici belirsizlikler, CRISPR-Cas9 teknolojisinin yaygın uygulamaya geçişinde dikkate alınması gereken önemli hususlar arasında yer almaktadır. Bu nedenle teknolojinin etkin ve güvenli bir şekilde kullanılabilmesi için moleküler düzeyde doğrulama çalışmaları, standart protokoller ve bilimsel temelli risk değerlendirmelerinin yapılması büyük önem taşımaktadır. Sonuç olarak, uygun etik yaklaşımlar ve bilimsel temellere dayalı regülasyon çerçeveleri eşliğinde değerlendirildiğinde, CRISPR-Cas9 teknolojisinin sürdürülebilir tarım, iklim değişikliğine uyum ve küresel gıda güvenliği hedeflerine uzun vadede önemli katkılar sağlayacağı açıktır. Gelişen genom düzenleme yaklaşımları ve ıslah programlarıyla entegrasyonu sayesinde, CRISPR-Cas9'un gelecekte modern bitki ıslahının temel araçlarından biri haline gelmesi beklenmektedir.

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Lens culinaris'te ABİYOTİK VE BİYOTİK STRES YANITLARININ OMİK TABANLI ANALİZİ VE ÇOKLU AĞ MODELLERİ

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ÖZET

Bu çalışma, mercimek (*Lens culinaris* Medik.) bitkisinin abiyotik ve biyotik stres koşullarına verdiği moleküler yanıtları, çok katmanlı omik yaklaşımlar ve sistem biyolojisi analizleri çerçevesinde kapsamlı biçimde değerlendirmektedir. Transkriptomik çalışmalar, tuzluluk, kuraklık, sıcaklık ve patojen kaynaklı streslerde iyon taşınımı (NHX1, SOS1, HKT1), ozmotik dengeleme (P5CS, BADH), protein koruma (HSP70, HSP90) ve patojen savunması (PR genleri, JA–SA sinyal yolları) gibi temel mekanizmaların aktive olduğunu göstermiştir. Yabani mercimek türlerinde NBS-LRR gibi direnç genlerinin kültür çeşitlerine göre daha yüksek düzeyde ifade edilmesi, biyotik stres toleransında önemli bir genetik kaynak potansiyeli ortaya koymaktadır. Çalışmada ayrıca WGCNA tabanlı birlikte ifade ağları incelenmiş, stresle ilişkili mTurquoise ve mYellow gibi modüllerin antioksidan savunma, hormon sinyallemesi, karbon metabolizması ve transkripsiyonel düzenleme süreçlerini eş zamanlı yönettiği belirlenmiştir. bZIP, NAC, MYB ve WRKY transkripsiyon faktörleri, stres toleransını şekillendiren başlıca "hub genler" olarak öne çıkmıştır. Çok katmanlı ağ modellemesi ve dinamik Bayesian ağ analizleri ise, stres yanıtının erken (ABA–SnRK2–DREB ekseni) ve geç (ROS temizleyici enzimler) olmak üzere iki temel aşamada gerçekleştiğini ortaya koymuştur. Transkriptom–proteom–metabolom entegrasyonu, gen ekspresyonundaki değişimlerin protein düzeyi ve metabolit birikimiyle bağlantısını doğrulamış; özellikle prolin, trehaloz ve fenolik bileşiklerin kuraklık altında belirgin şekilde arttığı gösterilmiştir. Fonksiyonel doğrulama çalışmalarında ise LcDREB2A ve LcNHX1 gibi genlerin aşırı ekspresyonunun stres dayanımını artırdığı deneysel olarak kanıtlanmıştır. Genel olarak bu çalışma, mercimekte stres toleransının karmaşık bir gen–protein–metabolit ağından oluştuğunu göstermekte ve modern ıslah programlarında kullanılabilecek kritik aday genleri, düzenleyici ağları ve biyokimyasal yolları çok yönlü bir bakış açısıyla tanımlamaktadır.

Anahtar Kelimeler: Çok katmanlı ağ modellemesi, stres toleransı, aday genler

OMICS-BASED ANALYSIS OF ABIOTIC AND BIOTIC STRESS RESPONSES AND MULTILAYER NETWORK MODELS IN *Lens culınarıs*

ABSTRACT

This study comprehensively evaluates the molecular responses of lentil (*Lens culinaris* Medik.) to abiotic and biotic stress conditions within the framework of multilayer omics approaches and systems biology analyses. Transcriptomic studies have shown that under salinity, drought, temperature, and pathogen-induced stresses, fundamental mechanisms such as ion transport (NHX1, SOS1, HKT1), osmotic adjustment (P5CS, BADH), protein protection (HSP70, HSP90), and pathogen defense (PR genes, JA–SA signaling pathways) are activated. The higher expression levels of resistance genes such as NBS-LRR in wild lentil species compared to cultivated varieties reveal an important genetic resource potential for biotic stress tolerance. The study also examined WGCNA-based co-expression networks and determined that stress-related modules such as mTurquoise and mYellow simultaneously regulate antioxidant defense, hormone signaling, carbon metabolism, and transcriptional regulation processes. Transcription factors including bZIP, NAC, MYB, and WRKY have emerged as the main hub genes shaping stress tolerance. Multilayer network modeling and dynamic Bayesian network analyses revealed that the stress response occurs in two main stages: an early stage involving the ABA–SnRK2–DREB axis and a late stage characterized by ROS-scavenging enzymes. Transcriptome–proteome–metabolome integration confirmed the association between changes in gene expression and protein levels as well as metabolite accumulation; in particular, proline, trehalose, and phenolic compounds were shown to increase markedly under drought stress. In functional validation studies, the overexpression of genes such as *LcDREB2A* and *LcNHX1* was experimentally proven to enhance stress tolerance. Overall, this study demonstrates that stress tolerance in lentil consists of a complex gene–protein–metabolite network and identifies critical candidate genes, regulatory networks, and biochemical pathways from a comprehensive perspective that can be utilized in modern breeding programs.

Keywords: Multilayer network modeling, stress tolerance, candidate genes

1. Stres-Spesifik Transkriptom Dinamikleri

Transkriptomik analizler, mercimeğin farklı stres koşullarına karşı nasıl tepki verdiğini moleküler düzeyde anlamak için güçlü bir araçtır. Bu analizler sayesinde, bitkinin stres sırasında hangi genleri aktive ettiği ya da baskıladığı, hangi biyolojik yolları kullandığı ve tolerans mekanizmasını nasıl şekillendirdiği ayrıntılı olarak ortaya konmaktadır. Farklı stres tipleri genellikle kendilerine özgü gen ifade düzenleri oluşturmaktadır. Bu nedenle RNA-Seq çalışmaları, su eksikliği, tuzluluk, sıcaklık değişimleri veya hastalık etmenleri gibi durumlarda devreye giren özel gen ağlarını tanımlamada kritik rol oynamaktadır (Zhang ve ark., 2019).

1.1.Tuz Stresi

Tuz stresine verilen moleküler yanıt, mercimekte iyon dengesinin korunması ve hücrelerin tuzluluk kaynaklı zararlardan korunması açısından kritik öneme sahiptir. Tolerant (*IG 4258*) ve hassas (*Precoz*) mercimek genotiplerinde yapılan karşılaştırmalı RNA-Seq analizleri, tuz stresinin belirli gen gruplarını güçlü biçimde aktive ettiğini göstermektedir. Bu çalışmalar, özellikle üç temel gen grubunun tuz stresine yanıt olarak yukarı yönlü ifade edildiğini ortaya koymuştur.

İyon taşınımı ve iyon dengeleme genleri: *NHX1, HKT1, SOS1*. Bu genler hücre içi sodyum ve potasyum dengesini düzenleyerek iyon homeostazını korumaktadır. Böylece tuzun hücrede toksik seviyeye ulaşmasını engellemektedir.

Osmotik koruma sağlayan genler: *P5CS, BADH*. Bu genler prolin ve betain gibi ozmoprotektanların sentezini artırarak hücrenin su kaybını azaltır ve metabolik dengeyi desteklemektedir.

Isı şok proteinleri (HSP) ve protein koruma mekanizmaları: *HSP70, HSP90*. Tuz stresinin yol açtığı protein hasarını sınırlayarak proteinlerin katlanmasını ve stabilitesini korur. Ayrıca LEA (Late Embryogenesis Abundant) protein ailelerine ait genlerin de tuzluluk ve kuraklık koşullarında belirgin şekilde arttığı gösterilmiştir. LEA proteinleri, stres altında hücre yapılarının korunmasına ve su eksikliği kaynaklı zararların azaltılmasına yardımcı olur. Bu sonuçlar genel olarak, mercimeğin tuz stresine karşı iyon düzenleme, ozmotik dengeleme ve protein koruma olmak üzere üç temel savunma stratejisi geliştirdiğini göstermektedir (Roy ve ark., 2014; Wang ve ark., 2020).

1.2.Biyotik Stres Yanıtları

Mercimek bitkisi, patojen saldırılarıyla karşılaştığında hızlı ve çok katmanlı bir savunma yanıtı geliştirir. RNA-Seq analizleri, bu savunma mekanizmalarının moleküler temelini ayrıntılı biçimde ortaya koymaktadır. Antraknoz etmeni *Colletotrichum truncatum* ile yapılan çalışmalarda, enfeksiyon sırasında iki önemli bitki savunma sinyal yolunun etkinleştiği görülmüştür: Jasmonat (JA) sinyal yolu ve Salisilik asit (SA) sinyal yolu.

Bu sinyal molekülleri, bitkide savunma yanıtını başlatan temel düzenleyicilerdir. JA ve SA sinyallemesinin eş zamanlı aktive olması, mercimeğin hem nekrotrofik hem de biyotrofik etmenlere karşı çok yönlü bir savunma stratejisi geliştirdiğini göstermektedir. Aynı çalışmalarda, enfeksiyon sırasında Pathogenesis-Related (PR) genlerinin belirgin biçimde arttığı tespit edilmiştir. PR proteinleri, bitki savunmasının ilk basamaklarında görev alır ve patojenleri doğrudan baskılayan enzimatik işlevlere sahiptir. Biyotik stres yanıtlarının anlaşılmasında yabani mercimek türlerinin incelenmesi de önemli bilgiler sağlamıştır. *Lens ervoides* ile kültüre alınmış *L. culinaris* genotiplerinin karşılaştırmalı transkriptom analizleri, yabani türlerin savunma genlerini çok daha güçlü şekilde aktive ettiğini göstermiştir. Özellikle: NBS-LRR (nucleotide-binding site–leucine-rich repeat) tipi direnç genlerinin ifade düzeyleri,

yabani türlerde kültür çeşitlerine göre 3–5 kat daha yüksektir. Bu yüksek ifade düzeyleri, yabani türlerin doğal ortamlarda daha fazla patojen baskısına maruz kalmaları nedeniyle genetik olarak daha güçlü savunma kapasitesi geliştirdiklerini göstermektedir. Bu bulgular, *L. ervoides* gibi yabani akrabaların biyotik stres toleransı için değerli genetik kaynaklar olduğunu ve mercimek ıslahında bu türlerin kullanılmasının önemini açıkça ortaya koymaktadır (Glazebrook, 2005; Sudheesh ve ark., 2016).

1.3. Çoklu Stres Etkileşimleri ve Ağ Analizi

Mercimek bitkisi doğal ortamlarda çoğu zaman tek bir stresle değil, kuraklık, tuzluluk, sıcaklık ve hastalık etmenleri gibi birden fazla stresle aynı anda karşı karşıya kalmaktadır. Bu nedenle son yıllarda yapılan transkriptom çalışmalarında, bitkinin eş zamanlı stres koşullarında nasıl bir gen ifade düzeni oluşturduğunu anlamak için sistem biyolojisi yaklaşımları kullanılmaktadır. Bu amaçla en yaygın kullanılan yöntemlerden biri, Weighted Gene Co-expression Network Analysis (WGCNA) adlı birlikte ifade ağ analizidir. WGCNA, benzer ifade paternlerine sahip genleri "modül" adı verilen kümeler halinde gruplar. Her modül, belirli biyolojik süreçlerle ilgili genleri içerir ve stres altında birlikte çalıştıkları düşünülmektedir (Langfelder ve Horvath, 2008).

2. Fonksiyonel Genomik ve Sistem Biyolojisi Entegrasyonu

Mercimek (*Lens culinaris Medik.*) gibi geniş ve karmaşık genom yapısına sahip bitkilerde, tek bir omik yaklaşımı kullanmak genellikle biyolojik süreçleri tam olarak anlamak için yeterli değildir. Bitkilerin streslere, gelişim süreçlerine veya çevresel değişikliklere nasıl yanıt verdiğini anlamak için genomik, transkriptomik, proteomik ve metabolomik gibi farklı veri katmanlarının bir arada değerlendirilmesi gerekmektedir. Bu nedenle son yıllarda fonksiyonel genomik ve sistem biyolojisi yaklaşımlarının entegrasyonu, mercimek ıslahı ve stres biyolojisi araştırmalarında yeni bir bakış açısı oluşturmuştur. Fonksiyonel genomik, genlerin hangi koşullarda nasıl ifade edildiğini, hangi proteinleri kodladığını, bu proteinlerin hangi metabolik yolları etkilediğini ve tüm bunların bitkinin fenotipine nasıl yansıdığını incelemeyi amaçlar. Bu yaklaşım, yalnızca gen varlığını belirlemekle kalmaz, aynı zamanda genlerin işlevini ve biyolojik önemini de ortaya koymaktadır. Sistem biyolojisi ise bu bilgileri daha geniş bir çerçevede değerlendirerek, gen protein metabolit etkileşimlerini dinamik ve çok katmanlı bir ağ (network) olarak ele alır. Böylece bitkinin belirli bir strese veya çevresel koşula verdiği yanıt, tekil gen davranışları üzerinden değil, tüm biyolojik sistemin ortak işleyişi üzerinden anlaşılabilir. Bu iki yaklaşım bir araya getirildiğinde, mercimekte: Stres toleransını yöneten temel genler, gen ve metabolitler arasındaki kritik bağlantılar, ağın merkezinde yer alan "hub genler" ve kompleks karakterlerin biyolojik temeli çok daha net biçimde ortaya konabilmektedir. Bu durum, modern ıslah çalışmalarında hedef gen seçimini, fonksiyonel belirteç geliştirilmesini ve moleküler düzeyde hassas ıslah stratejilerinin tasarlanmasını önemli ölçüde kolaylaştırmaktadır. Mercimek genomunda yapılan çalışmalar, transkriptomik, proteomik, ve metabolomik verilerin bir araya getirilmesinin, özellikle stres toleransı, verim ve kalite gibi kompleks karakterlerin çözümünde kritik olduğunu göstermektedir. Bitkiler çevresel streslere maruz kaldığında genlerdeki değişim yalnızca mRNA düzeyinde kalmaz. Aynı zamanda proteinlerin miktarı, yapısı ve işlevi de etkilenir. Bu nedenle transkriptomik (RNA-Seq) ve proteomik verilerin birlikte değerlendirilmesi, stres yanıtının daha bütüncül şekilde anlaşılmasını sağlar. Böyle bir entegrasyon, mRNA düzeyinde gözlenen artışların gerçekten protein düzeyine yansıyıp yansımadığını ortaya koyar. Metabolomik analizler, bitkilerin stres koşullarında ürettiği veya biriktirdiği küçük molekülleri (metabolitleri) inceleyerek, stres yanıtlarının biyokimyasal düzeyde nasıl şekillendiğini ortaya koyar. Bu analizler, gen ekspresyonunda gözlenen değişikliklerin hücresel metabolizmaya nasıl yansıdığını anlamak

açısından büyük önem taşır. Kuraklık stresine yönelik yapılan LC–MS/MS (sıvı kromatografisi–kütle spektrometrisi) temelli metabolomik çalışmalar, mercimek bitkisinin yapraklarında belirli metabolitlerin belirgin şekilde arttığını göstermektedir (Basu et al., 2023). Bu metabolitler arasında: Prolin, trehaloz, rafinoz ve fenolik bileşikler gibi stres toleransı ile ilişkili moleküller bulunmaktadır. Bu bileşikler, hücreyi kuraklığın neden olduğu oksidatif ve ozmotik zararlara karşı koruyan önemli savunma unsurlarıdır. Bu metabolitlerin artışı, transkriptom analizlerinde yukarı regüle olduğu belirlenen belirli genlerle doğrudan ilişkilidir. Dolayısıyla, gen ekspresyonu ile metabolit birikimini birlikte inceleyen gen–metabolit korelasyon analizleri, mercimekte stres toleransını belirleyen temel biyokimyasal yolların tanımlanmasında oldukça güçlü bir araçtır. Bu yaklaşımlar, ıslah programlarında hangi gen veya metabolitlerin hedeflenmesi gerektiğini belirlemede önemli avantaj sağlamaktadır (Gygi ve ark., 1999; Civelek ve Lusis, 2014; Basu ve ark., 2023).

3. Gen Etkileşim Ağları ve Önemli Düzenleyici Genler

3.1. Birlikte İfade (Co-Expression) Ağları

Mercimekte stres yanıtlarını anlamak için yalnızca tek tek genlerin ifade düzeylerini incelemek yeterli değildir. Bitki, stres koşullarında genellikle birlikte çalışan gen gruplarını devreye sokar. Bu nedenle transkriptom verilerinin ağ yapısı içinde analiz edilmesi, stres toleransını yöneten gen kümelerinin belirlenmesine olanak sağlar. Bu amaçla en sık kullanılan yöntemlerden biri Weighted Gene Co-expression Network Analysis (WGCNA) tekniğidir. WGCNA, benzer ifade düzeylerine sahip genleri "modül" adı verilen kümeler halinde toplar ve böylece stres altında birlikte çalışan gen grupları ortaya çıkarır. Mercimek için yapılan analizlerde birkaç önemli modül tanımlanmıştır:

"mTurquoise" Modülü: Bu modül, özellikle aşağıdaki gen gruplarını içermektedir:

Antioksidan savunma genleri: *SOD*, *POD*, *GST*. Bu genler, stres sırasında oluşan reaktif oksijen türlerini (ROS) temizleyerek hücreyi oksidatif hasardan korumaktadır.

mBlue Modülü: Bu modül ise hormon sinyallemesiyle ilgili genleri içermektedir: ABA (absisik asit), Etilen, Jasmonat (JA). Bu hormonlar, bitkinin stres algısı ve savunma tepkilerinin düzenlenmesinde önemli role sahiptir. Her modülün merkezinde, ağın işleyişini yönlendiren ve "hub gen" olarak adlandırılan temel düzenleyici genler bulunur. Bu hub genler genellikle transkripsiyon faktörleridir. Bu genlerin ağdaki merkezi konumu, stres toleransının düzenlenmesinde kritik rol oynadıklarını göstermektedir. Bu tür birlikte ifade ağ analizleri, mercimekte stres toleransını yöneten anahtar genleri belirlemede güçlü bir araçtır ve gelecekte ıslah çalışmalarında hedef gen seçimi için önemli bir temel sunmaktadır.

3.2. Anahtar Regülatör Transkripsiyon Faktörleri

Bitkiler stres koşullarına maruz kaldığında, çok sayıda gen aynı anda devreye girer. Bu geniş yanıtı yöneten en kritik gen gruplarından biri transkripsiyon faktörleridir. Transkripsiyon faktörleri, diğer genlerin açılıp kapanmasını kontrol ederek stres sırasında genetik yanıtın koordinasyonunu sağlar. Bu nedenle sistem biyolojisi analizlerinde TF'ler çoğunlukla ağın merkezinde yer alır ve "master regülatör" olarak adlandırılır. Mercimekte kuraklık, tuzluluk ve sıcaklık gibi stres koşullarında öne çıkan başlıca transkripsiyon faktörü aileleri şunlardır:

- bZIP (Basic Leucine Zipper) Ailesi

  Görevleri: ABA sinyallemesinin düzenlenmesi, su dengesinin kontrolü

  Örnek genler: *LcbZIP12, LcbZIP62*

Bu genler kuraklık ve tuzluluk streslerinde hücre içi su dengesini koruyan yolları aktive eder.

- NAC Ailesi (NAM–ATAF–CUC)

  Görevleri: Hücre duvarının dayanıklılığı, yaşlanma süreçleri, stres toleransı

  Örnek genler: *LcNAC67*, *LcNAC19*

NAC genleri özellikle kuraklık ve yüksek tuzluluk altında dayanıklılığı artıran yeniden yapılanma süreçlerini yönetir.

- MYB Ailesi

  Görevleri: Sekonder metabolit sentezi, fenolik bileşiklerin üretimi, antioksidan savunma

  Örnek genler: *LcMYB44*, *LcMYB108*

Bu genler oksidatif stresin azaltılmasında önemli rol oynayan metabolitlerin sentezini artırır.

- WRKY Ailesi

  Görevleri: Biyotik stres yanıtları, patojen savunması, PR genlerinin düzenlenmesi

  Örnek genler: *LcWRKY70*, *LcWRKY33*

WRKY faktörleri özellikle antraknoz ve Fusarium gibi hastalıklara karşı savunma yanıtını yönetir.

Bu transkripsiyon faktörleri stres sırasında yalnızca kendi işlevlerini yerine getirmekle kalmaz, aynı zamanda birbirleriyle oluşturdukları etkileşim ağları aracılığıyla çok daha geniş bir savunma mekanizmasını koordine eder. Özellikle bZIP–MYB–NAC etkileşimlerinin kuraklık toleransında "metabolik yeniden programlama" adı verilen, bitkinin tüm metabolizmasını stres koşullarına uyarlayan kilit mekanizmayı yönettiği bildirilmektedir. Dolayısıyla bu transkripsiyon faktörleri, mercimekte stres toleransının moleküler düzeyde anlaşılması ve ıslah programlarında hedef genlerin belirlenmesi açısından en kritik düzenleyici gen gruplarını oluşturmaktadır (Jakoby ve ark., 2002; Dubos ve ark., 2010; Rushton ve ark., 2010).

3.3. Sistem Biyolojisi Modelleri ve Dinamik Simülasyonlar

3.3.1. Ağ Tabanlı Modelleme

Mercimekte stres yanıtlarını anlamak için yalnızca tek tek genlerin veya metabolitlerin davranışlarını incelemek yeterli değildir. Bitki, stres sırasında genler, proteinler ve metabolitler arasında çok sayıda karşılıklı etkileşim içeren karmaşık bir biyolojik ağ oluşturur. Bu nedenle mercimek sistem biyolojisi araştırmalarında giderek daha fazla ağ tabanlı modelleme (network-driven modeling) yaklaşımı kullanılmaktadır. Bu modellerde, stres yanıtında rol oynayan tüm biyomoleküller genler, proteinler ve metabolitler birlikte ele alınır ve aralarındaki ilişkiler çok katmanlı (multi-layer) ağlar şeklinde gösterilir. Böylece stres altında hangi moleküler yolların birlikte çalıştığı ve hangi bileşenlerin ağın merkezinde yer aldığı daha net biçimde ortaya konur.

LentilDroughtNet adlı model, mercimeğin kuraklık stresine verdiği yanıtı sistem düzeyinde inceleyen kapsamlı bir ağ yapısıdır. Bu modelde: 312 gen, 58 metabolit, 45 protein arasındaki bağlantılar analiz edilmiştir. Ağın merkezinde özellikle bZIP–LEA–P5CS ekseninin yer aldığı görülmüştür. Bu eksen: bZIP → stres sinyallemesini, LEA proteinleri → hücreyi

kuruma ve su kaybına karşı korumayı, P5CS → prolin sentezini düzenleyerek ozmotik dengeyi sağlamayı kontrol eden kritik bileşenlerdir.

Bu sonuçlar, mercimekte kuraklık toleransının tek bir gen veya metabolitten ziyade birbirine bağlı çok sayıda molekülden oluşan karmaşık bir ağ tarafından yönetildiğini göstermektedir. Ağ tabanlı modelleme, bu tür karmaşık stres yanıtlarını çözmek ve gelecekte ıslah için hedeflenebilecek "anahtar bileşenleri" belirlemek açısından oldukça güçlü bir yaklaşımdır (Weckwerth ve Fiehn, 2002; Barabási ve ark., 2011; Zhu ve ark., 2013).

3.3.2. Dinamik Ağ Analizi

Bitkilerin stres koşullarına verdiği yanıtlar zamanla değişen ve birbirini takip eden aşamalardan oluşur. Bu nedenle, genlerin yalnızca bir zaman noktasındaki durumunu gösteren statik ağ analizleri, stres sürecinin tamamını açıklamak için yeterli değildir. Stres yanıtının zaman içindeki değişimini görmek için dinamik ağ modellerine ihtiyaç vardır. Bu amaçla mercimek çalışmalarında Dynamic Bayesian Network (DBN) modelleri kullanılmaktadır. DBN, farklı zaman noktalarında elde edilen gen ifade verilerini analiz ederek:

- ✓ genler arasındaki neden–sonuç ilişkilerini,
- ✓ belirli süreçlerin hangi sırayla aktive olduğunu,
- ✓ stres yanıtının erken ve geç evrelerde nasıl farklılaştığını

ayrıntılı biçimde ortaya koyar.

Mercimeğe uygulanan DBN analizleri, kuraklık ve tuzluluk gibi stres koşullarında iki önemli aşama olduğunu göstermiştir:

1. Erken stres yanıtı aşaması

Bu aşamada özellikle:

- ✓ ABA sinyal yolakları
- ✓ SnRK2 protein kinazları
- ✓ DREB transkripsiyon faktörleri

aktif durumdadır. Bu üçlü (ABA–SnRK2–DREB ekseni), bitkinin stresi algılamasını ve hızlı bir savunma yanıtı başlatmasını sağlar.

2. Geç stres yanıtı aşaması

Stres süreci ilerledikçe bitki daha çok oksidatif stresle mücadeleye odaklanır. Bu aşamada:

- ROS temizleyici (ROS-scavenging) genlerin (*SOD, CAT, APX* vb.) daha baskın hale geldiği görülür. Böylece hücrede biriken reaktif oksijen türleri azaltılarak hücre hasarı sınırlandırılır. Bu bulgular, mercimek ıslahında tüm stres sürecini tek bir aşama olarak değerlendirmek yerine, farklı stres fazlarında etkili olan genlerin ayrı ayrı hedeflenmesi gerektiğini göstermektedir. Erken yanıt genleri hızlı algılamayı, geç yanıt genleri ise uzun süreli dayanımı şekillendirdiği için her iki grup da ıslah açısından kritik öneme sahiptir (Windram ve ark., 2012; Friedman ve ark., 2000).

5.4. Fonksiyonel Gen Doğrulama Yaklaşımları

Fonksiyonel genomik entegrasyonunun son aşaması, belirlenen aday genlerin fonksiyonel validasyonudur. Mercimekte bu doğrulama şu yaklaşımlarla yapılmaktadır:

qRT-PCR: RNA-Seq ile belirlenen genlerin ifade düzeylerinin doğrulanmasında kullanılmaktadır.

Heterolog ekspresyon sistemleri (Arabidopsis, Medicago truncatula): Mercimekten izole edilen genlerin diğer model bitkilerde test edilmesi.

CRISPR/Cas9 veya VIGS (Virus-Induced Gene Silencing): Hedef genlerin susturulması veya düzenlenmesiyle fonksiyonun doğrudan test edilmesi.

Bu doğrulama adımları, sistem biyolojisi modellerinden elde edilen teorik tahminlerin deneysel olarak desteklenmesini sağlayarak mercimek ıslahında genetik hedeflerin güvenilirliğini artırmaktadır (Sakuma ve ark., 2002; Bustin ve ark., 2009).

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GÜNEŞ ENERJİ SANTRALLERİ İÇİN GELİŞTİRİLMİŞ XGBOOST ALGORİTMASIYLA KISA DÖNEM GÜÇ ÜRETİM TAHMİNİ

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ÖZET

Küresel enerji dönüşümü hedefleri doğrultusunda yenilenebilir enerji kaynaklarının şebekeye entegrasyonu, enerji sistemlerinde önemli bir zorluk olarak ortaya çıkmaktadır. Bu kaynaklar arasında güneş enerji santrallerinin (GES) payı hızla artmakla birlikte, meteorolojik değişkenlere bağlı kesintili üretim yapıları, şebeke kararlılığı ve yük dengeleme operasyonları açısından ciddi planlama gereksinimleri doğurmaktadır. Bu nedenle GES'lerin kısa dönemli güç üretiminin yüksek doğrulukla tahmin edilebilmesi hem teknik işletme güvenliği hem de enerji piyasalarında ekonomik verimlilik açısından kritik öneme sahiptir. Bu çalışmada, GES'lerin kısa dönem güç üretimini yüksek hassasiyetle tahmin etmek amacıyla makine öğrenmesi tabanlı sınıflandırma algoritmalarından XGBoost modeli kullanılmıştır. Modelin girdi vektörü; saatlik ortam sıcaklığı, güneş ışınımı, geçmiş fotovoltaik üretim değerleri ve ışınım kararlılığı gibi türetilmiş atmosferik özellikler kullanılarak oluşturulmuştur. Geliştirilen model, mevsimsel değişkenliğin tahmin performansı üzerindeki etkisini değerlendirmek amacıyla dört mevsim özelinde ayrı ayrı test edilmiştir. Elde edilen sonuçlar, en yüksek doğruluk seviyesinin yaz mevsiminde sağlandığını göstermekte olup, karekök ortalama hata (KOH), ortalama mutlak yüzdesel hata (OMYH) ve belirlilik katsayısı (R^2) sırasıyla 648.95 kW, %7.94 ve 0.99 olarak hesaplanmıştır. Buna karşın en düşük performans sonbahar döneminde gözlenmiş; KOH, OMYH ve R^2 değerleri sırasıyla 1332.02 kW, %10.95 ve 0.94 olarak belirlenmiştir. Yüksek R^2 değerleri ve düşük hata oranları, XGBoost modelinin GES'lerin doğrusal olmayan ve karmaşık üretim dinamiklerini başarıyla yakalayabildiğini ortaya koymaktadır. Bu bulgular, geliştirilen modelin santral operatörleri ve şebeke yöneticileri için güvenilir bir karar destek aracı olarak endüstriyel uygulamalarda etkin biçimde kullanılabileceğini göstermektedir.

Anahtar Kelimeler: Güneş Enerjisi, Güç Tahmini, Şebeke Kararlılığı, XGBoost, Makine Öğrenmesi

SHORT-TERM POWER PRODUCTION FORECASTING USING THE XGBOOST ALGORITHM DEVELOPED FOR SOLAR POWER PLANTS

ABSTRACT

In line with global energy transition goals, the integration of renewable energy sources into power grids has become a critical challenge. Among these sources, the role of photovoltaic (PV) power plants is steadily increasing; however, their intermittency driven by meteorological conditions creates significant planning difficulties in terms of grid stability and load balancing. Therefore, achieving accurate short-term forecasting of PV generation is essential for both operational reliability and economic efficiency in energy markets. In this study, the XGBoost algorithm, a machine learning–based classification method, is employed to predict the short-term power output of PV plants with high precision. The input vector of the model consists of hourly ambient temperature, solar irradiance, historical PV output, and derived atmospheric indicators such as irradiance stability. To investigate the influence of seasonal variability on forecasting accuracy, the proposed model is evaluated separately for four distinct seasons. The results demonstrate that the highest prediction accuracy is achieved during the summer period, with a root mean square error (RMSE) of 648.95 kW, mean absolute percentage error (MAPE) of 7.94%, and coefficient of determination (R^2) of 0.99. Conversely, the lowest performance is observed in autumn, where RMSE, MAPE, and R^2 are calculated as 1332.02 kW, 10.95%, and 0.94, respectively. The high R^2 values and low error metrics confirm the strong capability of XGBoost in capturing the nonlinear and complex generation dynamics of PV systems. These findings indicate that the developed model can serve as a robust and effective decision-support tool suitable for industrial applications by grid operators and power plant managers.

Keywords: Solar Energy, Power Forecasting, Grid Stability, XGBoost, Machine Learning

1.GİRİŞ

Günümüzde, fosil yakıtların tükenmesi ve artış gösteren sera gazı emisyonları nedeniyle, yenilenebilir enerji kaynaklarının yaygınlaşması hız kazanmıştır (Taşdemir ve ark., 2024). En yaygın kullanılan yenilenebilir enerji kaynaklarından biri olan fotovoltaik enerji, enerji sistemlerinin sürekli, istikrarlı ve ekonomik çalışmasında önemli bir rol oynamaktadır (Lin ve ark., 2022). 2025 yılı Eylül ayı itibarıyla Türkiye'nin kurulu gücü 121.418 MW'a ulaşmış olup güneş enerjisinin oranı %19,9 olarak gerçekleşmiştir. 2024 yılı için elektrik üretiminin kaynaklara göre dağılımı ise Şekil 1.1'de verilmiştir (T.C. Enerji ve Tabii Kaynaklar Bakanlığı, 2025).



Şekil 1.1. 2024 yılı elektrik üretiminin kaynaklara göre dağılımı

Fotovoltaik enerji üretimindeki belirsizlik ve değişkenlik nedeniyle, büyük ölçekli fotovoltaik sistemlerin şebekeye bağlanmasında önemli zorluklar bulunmaktadır (Maghami ve ark., 2016). Fotovoltaik enerjinin dalgalanması ve kesintileri, mevcut elektrik sistemlerinde beklenmedik kayıplara neden olabilir (Liu ve ark., 2018). Ayrıca, fotovoltaik güç sistemlerinin dengesiz yapısı elektrik kesintilerine, gerilim dalgalanmalarına ve şebekede verim kayıplarına yol açabilir. Bu nedenle, fotovoltaik güç çıkışının doğru tahmini ve fotovoltaik gücün şebekeye entegrasyonunun kolaylaştırılması gibi konular, fotovoltaik güç üretiminde önemli araştırma alanları olarak ortaya çıkmıştır (Saber ve ark., 2014).

Yapay zeka teknolojisindeki gelişmelerin bir sonucu olarak, fotovoltaik güç tahmini çok kısa vadeli, kısa vadeli, orta vadeli ve uzun vadeli dönemlerde gerçekleştirilmektedir (Li ve ark., 2020). Fotovoltaik güç tahmini için kullanılan dört farklı zaman aralığı ve amaçları Tablo 1.1'de verilmiştir (Elsinga ve Van Sark, 2017).

Tablo 1.1. Farklı zamanlarda fotovoltaik güç tahmininin uygulanabilirliği

Tahmin dönemleri	Periyot	Amaçlar
Çok kısa vadeli dönem	1 saniye ile 15 dakika arası	Yük takibi, yedek kapasite planlaması, güç kalitesi
Kısa vadeli dönem	15 dakika ile 1 saat arası	Piyasa belirlenmesi, yük takibi, yedek kapasite planlaması
Orta vadeli dönem	1 saat ile 1 gün arası	Piyasa belirlenmesi, temel yük planlaması
Uzun vadeli dönem	1 gün sonra tahmin	Enerji yönetimi, güç kapasitesinin dağıtımı

İlgili literatür çalışmaları incelendiğinde; günlük fotovoltaik güç tahmini çalışmalarında YSA ile JAYA–YSA hibrit modelinin karşılaştırıldığı ve hibrit modelin daha yüksek tahmin doğruluğu sağladığının raporlandığı görülmektedir (Irmak ve ark., 2024). Fotovoltaik güç tahmini kapsamında en iyi performansın Otomatik Regresif Entegre Hareketli Ortalama (OREHO) modeli tarafından elde edildiği; modelin KOH ve OMH değerlerinin sırasıyla 821,6 W ve 699,9 W olarak hesaplandığı bildirilmektedir (Das, 2021). Meteorolojik değişkenlere ek olarak PM10 parametresinin de modele dâhil edildiği bir diğer çalışmada, PM10'un fotovoltaik güç tahmini üzerindeki etkisi değerlendirilmiştir (Irmak ve ark., 2023).

Öğretme–Öğrenme Tabanlı Optimizasyon (TLBO) algoritması ile gerçekleştirilen fotovoltaik güç tahmini çalışmalarında ise hata ölçütü olarak KOH ve OMYH kullanılmıştır (Taşdemir, 2024). Haftalık tahmin uygulamalarında bağıl nem, yağış, ortam sıcaklığı, güneşlenme süresi ve bulutluluk miktarı gibi meteorolojik değişkenlerin giriş parametreleri olarak kullanıldığı belirtilmektedir (Moreira ve ark., 2021). Ayrıca geçmiş fotovoltaik güç, ortam sıcaklığı ve güneş ışınımı verilerinin kullanıldığı bir çalışmada Genetik Algoritma (GA) ile başarılı tahmin sonuçları elde edilmiştir (Ermiş ve Taşdemir, 2025). Uzun vadeli fotovoltaik güç tahmini için Kapılı Tekrarlayan Birimler (KTB) ve Uzun Kısa Süreli Bellek (UKSB) modelleri kullanılmış; bu modeller için sırasıyla R^2=0,987, OMH (%)=8,86 ve R^2=0,986, OMH (%)=8,77 değerleri rapor edilmiştir (Khatib ve ark., 2022).

Bu çalışmada, güneş enerji santrallerinin kesintili üretim karakteristiğinin şebeke üzerindeki olumsuz etkilerini en aza indirmek ve güç üretim tahmin doğruluğunu artırmak amacıyla XGBoost algoritmasına dayalı kısa vadeli tahmin modeli geliştirilmiştir. Önerilen yaklaşımda, ham verilerin bilgi taşıma kapasitesini artırmak amacıyla özellik mühendisliği (feature engineering) süreçleri uygulanmıştır. Bu süreçte, literatürdeki yaygın meteorolojik girdilere (sıcaklık, güneş ışınımı) ek olarak, atmosferik geçirgenliğin ve bulutluluk değişimlerinin bir göstergesi olan ışınım kararlılığı ile çevresel etkenlerin sisteme kümülatif etkisini yansıtan verimlilik faktörü parametreleri türetilerek modele dahil edilmiştir. Çalışma kapsamında, mevsimsel etkilerin model performansı üzerindeki değişimini analiz etmek üzere veriler mevsimsel bazda sınıflandırılmış ve modelin başarısı dört farklı mevsim için ayrı ayrı test edilmiştir. Elde edilen sonuçlar, Karekök Ortalama Hata (KOH), Ortalama Mutlak Yüzdesel Hata (OMYH) ve Belirlilik Katsayısı (R^2) gibi istatistiksel hata metrikleri kullanılarak değerlendirilmiştir.

2. ARAŞTIRMA VE BULGULAR

2.1. XGBoost Algoritması

Tianqi Chen ve Carlos Guestrin'in 2016 yılında geliştirdiği algoritma, Gradyan Artırma (Gradient Boosting) temelli, ölçeklenebilir ve yüksek performanslı bir makine öğrenmesi yöntemidir (Chen ve Guestrin, 2016). XGBoost, karar ağaçlarını ardışık olarak eğiterek ve her adımda bir önceki modelin hatalarını düzelterek güçlü bir tahmin yapısı oluşturur. XGBoost'u diğer topluluk öğrenme yöntemlerinden ayıran ve bu çalışmada tercih edilmesini sağlayan en önemli özellik, modelin karmaşıklığını kontrol altında tutan regülasyon yeteneğidir. Bu prosedür, modelin eğitim verisine aşırı uyum sağlamasını engelleyerek genelleştirme başarısını artırır (Friedman, 2006). Modelin amaç fonksiyonu (L_Ω), eğitim hatasını ölçen kayıp fonksiyonu (L) ve karmaşıklığı cezalandıran regülasyon teriminden (Ω) oluşur ve Denklem 1 ile ifade edilir.

$$L_\Omega(F_M) = \sum_{i=1}^{N} L(y_i, F_m(X_i)) + \sum_{m=1}^{M} \Omega(f_m) \quad (1)$$

Burada N örnek sayısını, L ise tahmin edilen değer ile gerçek değer arasındaki farkı ölçen kayıp fonksiyonu temsil eder. Algoritmanın kararlılığını artıran regülasyon terimi Ω ise, yaprak (düğüm) sayısı (J) ve yaprak ağırlıklarının (W) L2 normu kullanılarak Denklem (2)'deki gibi hesaplanır.

$$\Omega(f_m) = \Upsilon Jm + \frac{1}{2}\lambda \|W\|^2 \quad (2)$$

Eşitlikteki Υ parametresi bir düğümün bölünmesi için gereken minimum kayıp fonksiyonunu kontrol ederken, λ parametresi yaprak ağırlıklarını dengeleyerek modelin varyansını düşürür. Ayrıca algoritma, optimizasyon sürecinde kayıp fonksiyonunun ikinci dereceden Taylor serisi açılımını kullanır. Bu yaklaşım, hem birinci türev (gradyan) hem de ikinci türev (Hessian) bilgisinden yararlanarak standart gradyan iniş yöntemlerine göre daha hızlı ve kararlı bir yakınsama sağlar.

2.2. Deneysel Çalışmalar

Bu çalışmada İç Anadolu Bölgesi'nde faaliyet gösteren 25 MW kurulu güce sahip bir GES'ten elde edilen saha verileri kullanılmıştır. Veri seti, 1 Mart 2024 – 28 Şubat 2025 tarih aralığını kapsamakta olup, santralin SCADA (Merkezi Gözetim, Kontrol Ve Veri Toplama Sistemi) sisteminden kaydedilen 1 saatlik fotovoltaik güç üretim (kW) değerleri ile eş zamanlı olarak meteoroloji istasyonundan alınan ortam sıcaklığı (°C) ve güneş ışınımı (W/m²) verilerini içermektedir. Ham veriler, modelin öğrenme başarısını artırmak amacıyla ön işleme sürecine tabi tutulmuştur. Bu süreçte sensör hatalarından kaynaklanan kayıp veriler, gece saatlerinde oluşan gürültülü veriler (pozitif üretim hataları) ve santral kapasitesini aşan aykırı değerler eğitim veri setinden ayıklanmıştır. Modelin girdi vektörünü güçlendirmek amacıyla özellik mühendisliği (feature engineering**)** uygulanmış, geçmiş üretim verileri, ışınım kararlılığı ve zamansal döngüsellik (günlük/mevsimsel) sisteme yeni özellikler olarak eklenmiştir. Modelin genelleme yeteneğini doğrulama amacıyla veri seti, zaman serisi bütünlüğü korunarak kronolojik sırayla %70 eğitim ve %30 test seti olarak ayrılmıştır. Tüm süreçler Python ortamında gerçekleştirilmiştir. Model performansının değerlendirilmesinde temel metrikler olarak, Karekök Ortalama Hata (KOH), Ortalama Mutlak Yüzdesel Hata (OMYH) ve Belirlilik Katsayısı (R^2) tercih edilmiştir.

Denklem 3, tahmin edilen değerler ile gerçek değerler arasındaki farkların karesel ortalamasının karekökünü ifade eder. (Ermiş ve Taşdemir, 2025).

$$\text{KOH} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - p_i)^2} \quad (3)$$

Denklem 4, hataların mutlak büyüklüğünün gerçek değerlere oranını yüzdesel olarak ifade eder. (Ermiş ve Taşdemir, 2025).

$$\text{OMYH} = \frac{1}{N}\sum_{i=1}^{N}\frac{|y_i - p_i|}{p_i} \text{ x } 100 \quad (4)$$

Denklem 5, modelin, bağımlı değişkendeki varyansı açıklama oranını gösterir.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - p_i)^2}{\sum_{i=1}^{n}(y_i - g_i)^2} \quad (5)$$

İlgili eşitliklerde; n toplam gözlem (veri) sayısını, y_i i. zaman adımındaki gerçek üretim değerini, p_i model tarafından tahmin edilen üretim değerini ve g_i $g$erçek üretim değerlerinin aritmetik ortalamasını temsil etmektedir.

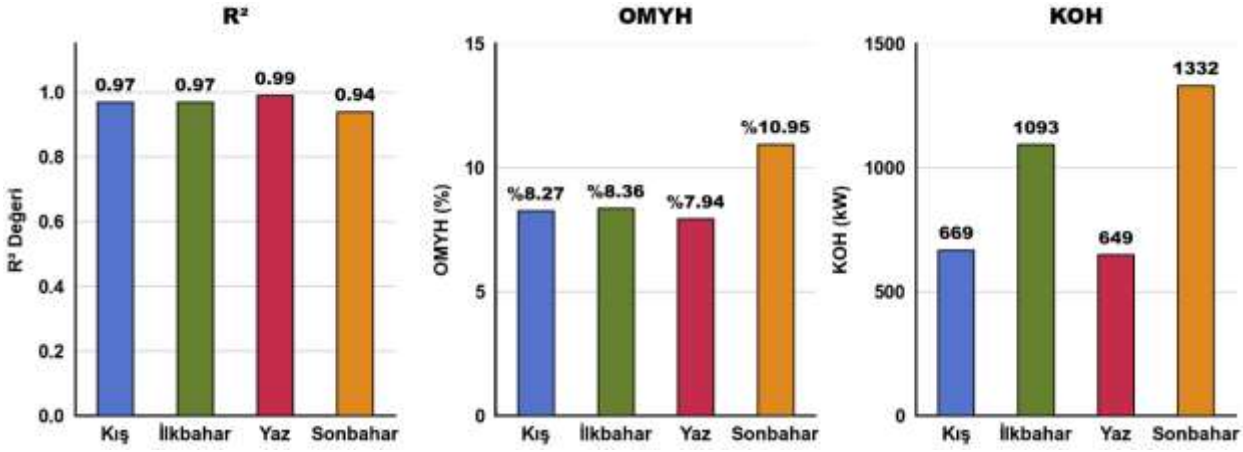
2.3. Deneysel Sonuçlar

Geliştirilen XGBoost modelinin yaz, ilkbahar, kış ve sonbahar dönemlerindeki kısa dönem tahmin performansını, güvenilirliğini ve genelleme kabiliyetini değerlendiren karşılaştırmalı metrik sonuçları Tablo 2.1'de verilmiştir.

Tablo 2.1. Modelin mevsimsel performans karşılaştırması

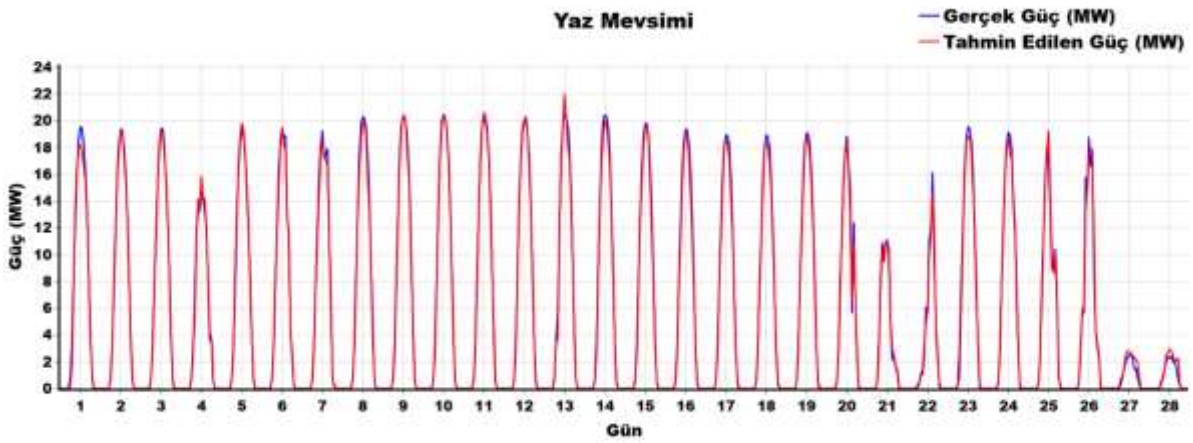
Mevsim	KOH (kW)	OMYH (%)	R^2
Yaz	648.95	7.94	0.99
İlkbahar	1093.28	8.36	0.97
Sonbahar	1332.02	10.95	0.94
Kış	668.98	8.27	0.97

Tablo 2.1'deki bulgular ve performans metriklerinin mevsimsel değişimlerinin sunulduğu Şekil 2.1 incelendiğinde, geliştirilen XGBoost modelinin tüm mevsimlerde 0.94'ün üzerinde R^2skoruna ulaşarak yüksek bir genelleme performansı sergilediği görülmektedir. KOH değerinin 648.95 kW olduğu yaz mevsimindeki 0.99'luk yüksek uyumun yanı sıra atmosferik koşulların değişkenlik gösterdiği ve KOH'un 1332.02 kW ile zirveye ulaştığı sonbahar döneminde dahi model, 0.94 seviyesindeki başarısını koruyarak verideki değişkenliği açıklama gücünü kanıtlamıştır. Mevsimsel koşullar ve KOH miktarları değişse de OMYH değerlerinin %7.94 ile %10.95 arasında düşük bir yüzdede seyretmesi, modelin farklı iklim profillerine ve güç değerlerine karşı kararlı bir yapı sergilediğini göstermektedir.

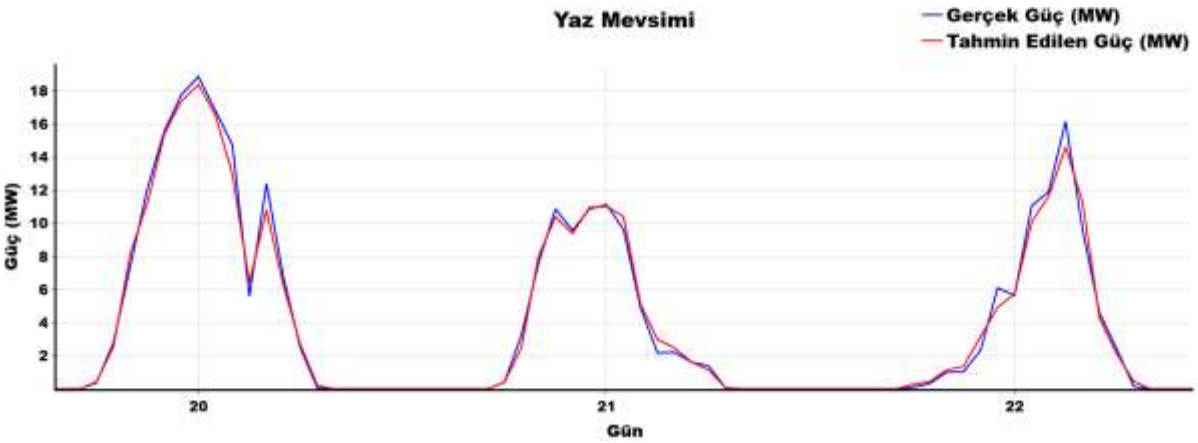


Şekil 2.1. R², KOH ve OMYH mevsimsel karşılaştırılması

Performans metrikleri detaylı olarak incelendiğinde, mevsimsel koşullara bağlı olarak istatistiksel farklılıklar ortaya çıktığı görülmektedir. Söz konusu farklılıklar içerisinde en dikkat çekici performansa, modelin en yüksek tahmin doğruluğunu yakaladığı yaz mevsiminde ulaşılmıştır. Bu dönemde, KOH ve OMYH sırasıyla 648.95 kW ve %7.94 olarak en düşük hata oranları gözlemlenmiş aynı zamanda 0.99 ile en yüksek belirlilik katsayısı elde edilmiştir. Bu başarının altında yatan temel faktörün, yaz aylarındaki güneş ışınımı verilerinin daha düzenli ve tahmin edilebilir bir karakteristik göstermesi olduğu değerlendirilmektedir. Şekil 2.2 ve Şekil 2.3, yaz mevsimi için gözlemlenen gerçek ve tahmin edilen güç eğrileri arasındaki performansı görsel olarak teyit etmektedir.

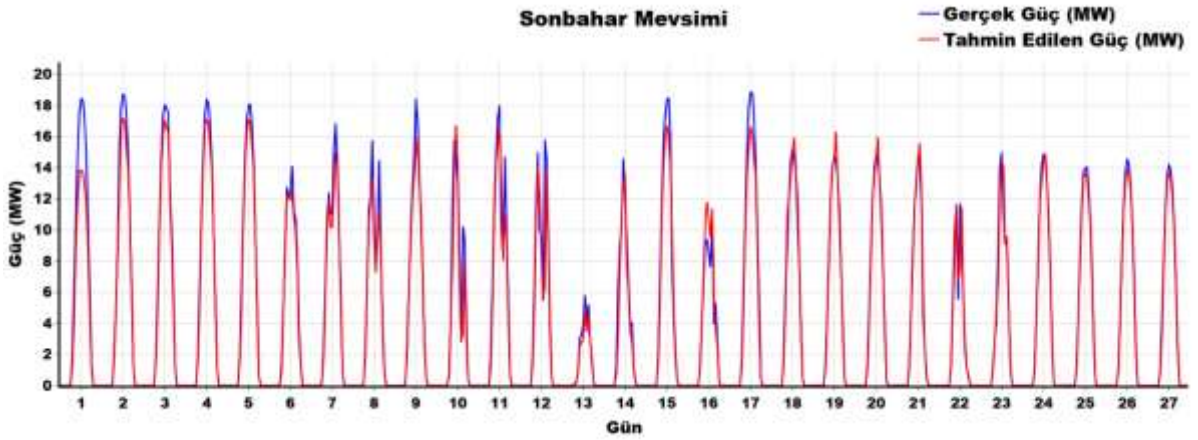


Şekil 2.2. Yaz mevsiminde gerçek ve tahmin edilen güç değişimleri



Şekil 2.3. Yaz mevsiminde kesiti alınmış gerçek ve tahmin edilen güç değişimleri

Buna karşılık, tüm mevsimler içerisinde en zorlu dönem olarak belirlenen sonbaharda, artan meteorolojik belirsizlikler ve değişken bulutluluk gibi koşullara bağlı olarak model performansı en yüksek hata değerlerine KOH = 1332.02 kW, OMYH = %10.95 ve en düşük $R^2 = 0.94$ değerine gerilemiş olsa da, Şekil 2.4 ve Şekil 2.5'te görülen yüksek dalgalanmalara karşın XGBoost algoritmasının ani bulut geçişlerinden kaynaklanan keskin değişimleri yakalamayı başarması, modelin yüksek frekanslı değişimlere karşı tahmin kabiliyetinin güçlü olduğunu ve genel trendi koruyabildiğini göstermektedir.

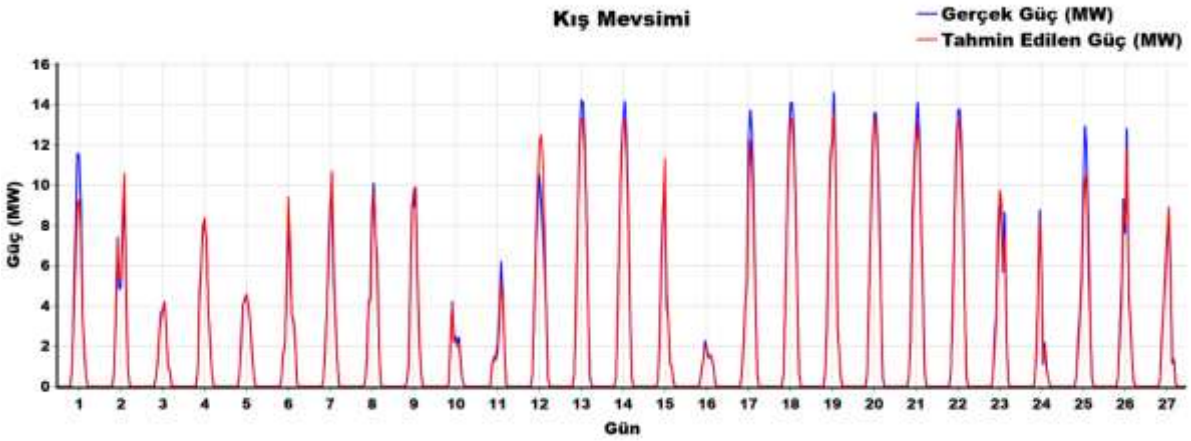


Şekil 2.4. Sonbahar mevsiminde gerçek ve tahmin edilen güç değişimleri

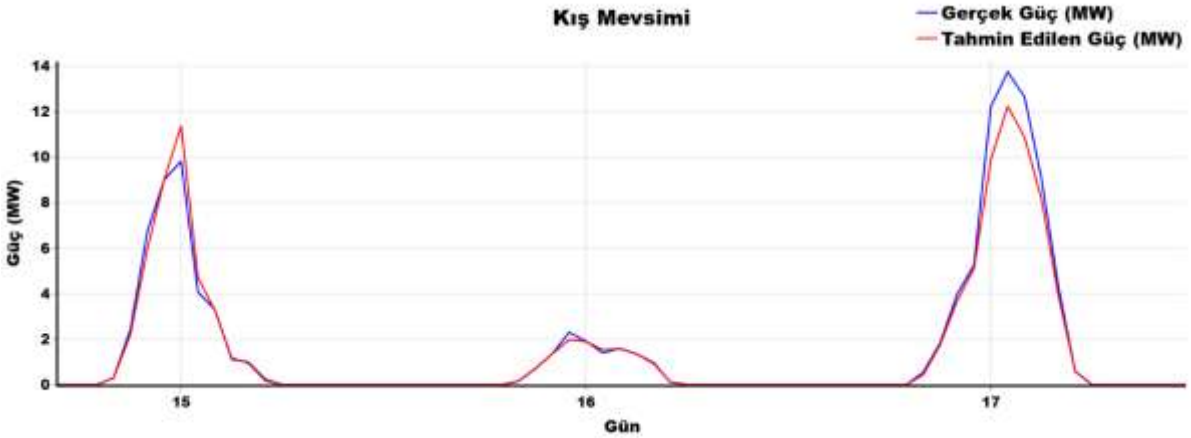


Şekil 2.5. Sonbahar mevsiminde kesiti alınmış gerçek ve tahmin edilen güç değişimleri

Kış mevsimi düşük ışınım seviyelerine rağmen KOH = 668.98 kW, OMYH = %8.27 ve $R^2 = 0.94$ değeri ile istikrarlı bir performans sergileyen modelin başarısının sadece yüksek üretimlerle sınırlı kalmayıp kapalı veya yağışlı günlerdeki ani değişimleri de başarıyla yakalaması, sistemin meteorolojik değişkenliğe karşı duyarlılığını kanıtlamaktadır.

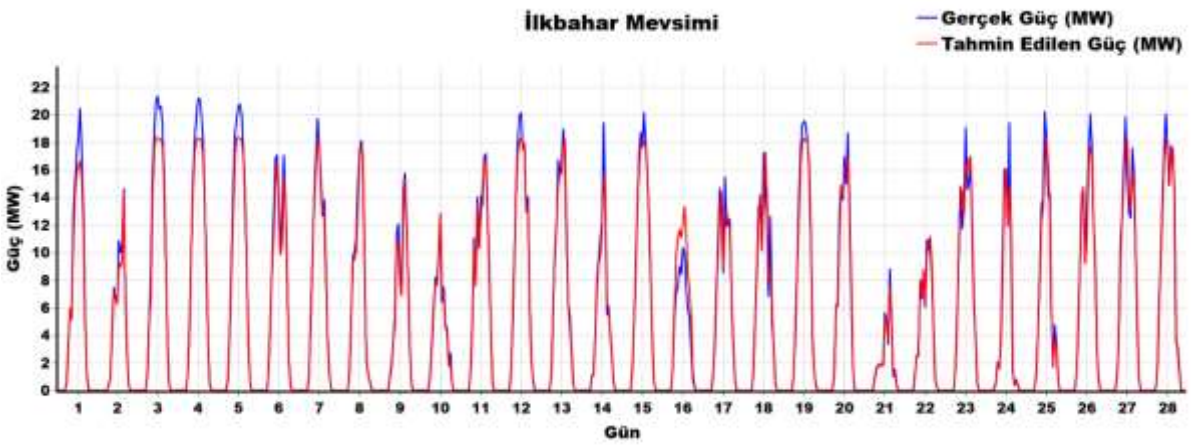


Şekil 2.6. Kış mevsiminde kesiti alınmış gerçek ve tahmin edilen güç değişimleri



Şekil 2.7. Kış mevsiminde kesiti alınmış gerçek ve tahmin edilen güç değişimleri

Sonbahardan sonra en yüksek hata oranlarının gözlemlendiği KOH = 1093.28 kW, OMYH = %8.36 ve $R^2 = 0.97$ değerlerinin kaydedildiği ilkbahar mevsiminde, modelin gün ortası zirve üretim anlarını düşük tahmin etmesine karşın gün doğumu ve gün batımı süreçlerindeki çizgisel artış ve azalış dinamiklerini yüksek bir başarıyla yakaladığı Şekil 2.8 ve Şekil 2.9'da görülmektedir.



Şekil 2.8. İlkbahar mevsiminde gerçek ve tahmin edilen güç değişimleri



Şekil 2.9. İlkbahar mevsiminde kesiti alınmış gerçek ve tahmin edilen güç değişimleri

3. SONUÇ

Bu çalışmada türetilmiş veriler olan ışınım kararlılığı ve verimlilik katsayısının kullanıldığı özellik mühendisliği süreci, XGBoost algoritmasının güçlü öğrenme yapısıyla birleştirilerek güneş enerjisi üretiminin doğrusal olmayan karmaşık dinamiklerini modellemede etkili ve üstün bir performans ortaya konmuştur. Geliştirilen model, tüm mevsimsel döngülerde 0.94'ün üzerinde bir belirlilik katsayısı ve %11 in altında düşük bir ortalama mutlak yüzde hataya ulaşarak, yalnızca atmosferik koşulların durağan ve tahmin edilebilir olduğu dönemlerde değil, aynı zamanda değişkenliğin ve atmosferik belirsizliğin zirveye ulaştığı ilkbahar ve sonbahar aylarında da istikrarlı ve güvenilir bir tahmin yeteneği sergilemiştir. Özellikle bulutlanma ve ani hava olaylarının sıkça yaşandığı günlerde hata oranlarında kısmi artışlar görülse de modelin üretim profilindeki ani artış ve azalış trendlerini doğru bir şekilde takip ettiği ve verideki anlık gürültüye rağmen ana üretim sinyalini yüksek bir doğrulukla yakaladığı gerçekleştirilen grafiksel analizlerle doğrulanmıştır. Elde edilen bu yüksek tahmin başarısı, modelin sağladığı teknik doğruluğun çok ötesine geçerek enerji yönetimi ve sistem güvenliği açısından da somut ve kritik faydalar sunmaktadır. Nitekim güç üretimindeki dalgalanmaların önceden ve yüksek hassasiyetle tahmin edilmesi, şebeke operatörlerinin güç dengeleme sistemlerini ve yük tevzi işlemlerini çok daha verimli yönetmesini sağlamakta ve şebekede oluşabilecek ani güç dengesizliklerine karşı hazırlıklı olunmasına imkan tanımaktadır. Bu gelişmiş öngörü yeteneği, inverter ve trafo gibi hassas güç donanımlarının

ani yüklenmeler sonucu maruz kaldığı aşırı ısınmayı ve mekanik yıpranmayı engelleyerek sistemin bakım maliyetlerini önemli ölçüde düşürmekte ve tesisin operasyonel kullanım ömrünü uzatmaktadır. Sonuç olarak bu çalışma, önerilen yaklaşımın sadece yüksek doğruluklu bir tahmin aracı değil, aynı zamanda yenilenebilir enerji kaynaklarının elektrik şebekesine entegrasyonunu kolaylaştıran, arz güvenliğini destekleyen ve tesislerin operasyonel verimliliğini artıran stratejik bir karar destek mekanizması olduğunu kanıtlamaktadır.

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ÖZET

Hastaneler, sağlık hizmeti sunarken çevre üzerinde önemli etkiler yaratabilecek atıklar üretmektedir. Bu atıklar enfekte, kimyasal, radyoaktif veya evsel nitelikte olabilmektedir. Özellikle tıbbi ve tehlikeli atıklar hem insan sağlığı hem de çevre açısından ciddi riskler taşımaktadır. Çevresel sürdürülebilirlik anlayışı, bu atıkların azaltılmasını, güvenli şekilde toplanmasını, taşınmasını, ayrıştırılmasını ve bertaraf edilmesini gerektirmektedir. Atık yönetimi süreçlerinin yasal mevzuata uygun, etkin ve çevre dostu yöntemlerle yürütülmesi sürdürülebilirliğe katkı sağlamaktadır. Ayrıca hastanelerde geri dönüşüm uygulamalarının yaygınlaştırılması, hastane personelinin eğitilmesi ve teknolojik çözümlerden faydalanılması hem çevresel etkilerin azaltılmasına hem de kaynakların verimli kullanılmasına katkıda bulunabilinecektir. Yeşil hastane uygulamaları ve enerji geri kazanım sistemleri gibi çevre dostu teknolojiler, sürdürülebilir sağlık hizmetlerinin geleceği açısından umut verici adımlar olarak değerlendirilmektedir. Sonuç olarak, hastane atıklarının etkin ve doğru yönetimi yalnızca çevrenin korunmasına değil, aynı zamanda sağlık sistemlerinin uzun vadeli sürdürülebilirliğine de hizmet eden temel bir unsurdur. Bu çalışma, çevresel sürdürülebilirliğin sağlanmasında hastane atıklarının etkisini analiz etmeyi amaçlamakta; aynı zamanda hastane kaynaklı atıkların yönetimine yönelik çözüm önerileri sunmaktadır.

Anahtar kelimeler: Sürdürülebilirlik, Yeşil Hastane, Hastane Atıkları, Atık Yönetimi.

HOSPITAL WASTE IN THE CONTEXT OF ENVIRONMENTAL SUSTAINABILITY

ABSTRACT

Hospitals produce waste that can have significant impacts on the environment while providing healthcare services. This waste can be infectious, chemical, radioactive, or domestic in nature. Medical and hazardous waste, in particular, poses serious risks to both human health and the environment. The concept of environmental sustainability requires that this waste be reduced, collected, transported, separated, and disposed of safely. Waste management processes that are legally compliant, effective, and environmentally friendly contribute to sustainability. Furthermore, promoting recycling practices in hospitals, training staff, and utilizing technological solutions can contribute to both reducing environmental impacts and efficient use of resources. Environmentally friendly technologies, such as green hospital practices and energy recovery systems, are considered promising steps for the future of sustainable healthcare services. In conclusion, the effective and proper management of hospital waste is a fundamental element that not only protects the environment but also serves the long-term sustainability of healthcare systems. This study aims to analyze the impact of hospital waste on ensuring environmental sustainability; it also offers solutions for managing hospital-generated waste.

Keywords: Sustainability, Green Hospital, Hospital Waste, Waste Management.

1.GİRİŞ

Dünya, canlı ve cansız varlıkların birlikte yaşadığı bir ekosistemdir ve bu varlıklar birbirleriyle sürekli etkileşim halindedir. İnsanlar binlerce yıldır bu ekosistemle iç içe yaşamlarını sürdürmüş, ancak zamanla çevre üzerinde önemli etkiler yaratmıştır. Sanayileşme ve fosil yakıt kullanımıyla atmosfere zararlı gazların salınımı artmış, bu da çevre kirliliği ve bozulmasına yol açmıştır. Günümüzde ise hızlı nüfus artışı, aşırı enerji kullanımı ve bilinçsiz kaynak tüketimi nedeniyle insan etkisi küresel boyuta ulaşmıştır(Çilhoroz & Işık, 2018).

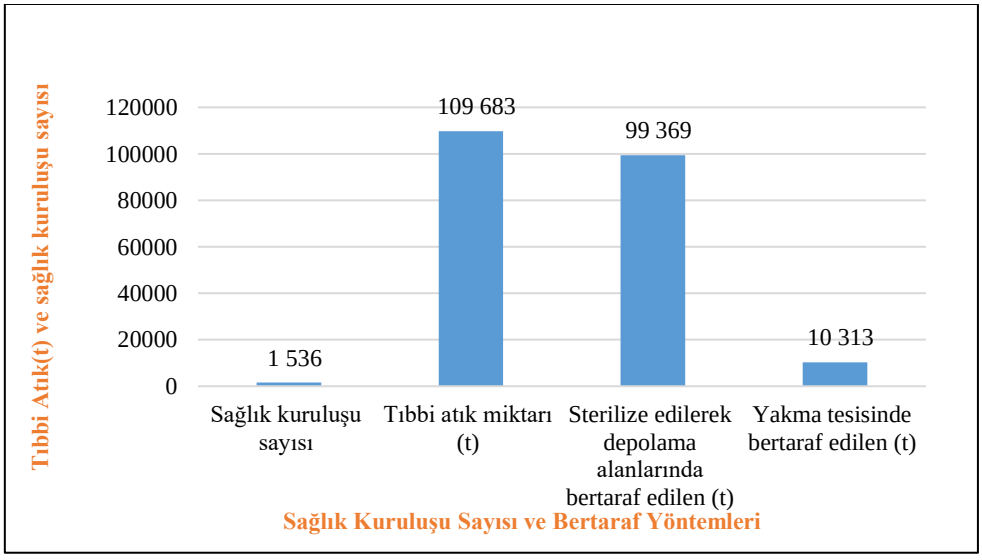
Sağlık sektöründe, hastanelerde servis edilen ancak tüketilmeyen gıdalar önemli bir atık kaynağıdır. Bu atıklar hem finansal kayıplara hem de çevresel sorunlara yol açmaktadır. Sağlık kurumlarında gıda atıklarının etkin yönetimi; atık miktarının azaltılması, ihtiyaç sahiplerine dağıtım, hayvan besleme ve kompostlama gibi yöntemlerle sürdürülebilirliği desteklemektedir. Bu bağlamda, sağlık sektöründe çevre dostu ve sürdürülebilir gıda atık yönetimi uygulamalarının geliştirilmesi önem taşımaktadır. Atık yönetimi, küresel, bölgesel, ulusal ve yerel düzeylerde çok katmanlı bir yapıya sahiptir. Dünya üzerinde Basel Sözleşmesi (tehlikeli atıklar vb.), Stockholm Sözleşmesi (kalıcı kirleticiler vb.) ve Minamata Sözleşmesi (civa) gibi uluslararası anlaşmalar ve Dünya Sağlık Örgütü(WHO) gibi uluslararası kuruluşlar bulunmaktadır. Avrupa Birliği ise Yeşil Anlaşma, Döngüsel Ekonomi Eylem Planı ve Plastik Stratejisi gibi direktif ve stratejilerle atıkların yönetimini düzenlemektedir. Bölgesel iş birliği kapsamında ise Batı Balkanlar için ekonomik ve çevresel ortaklık programları geliştirilmiştir. Ulusal düzeyde yasalar, stratejiler, eylem planları ve yönlendirme komiteleri atık yönetiminin temelini oluştururken, yerel topluluklar da sıfır atık sivil toplum kuruluşları, iş sektörü ve bilimsel topluluklar gibi paydaşlarla bu sürece katkı sağlamaktadır. Böylece atık yönetimi, farklı seviyelerdeki iş birliği ve düzenlemelerle bütüncül bir şekilde ele alınmaktadır. Nüfus artışı ve tek kullanımlık ürünlerin yaygınlaşmasıyla sağlık kurumlarında atık miktarı artmıştır. Hastanelerde sürdürülebilirlik için tıbbi ve gıda atıklarının uygun şekilde yönetilmesi önemlidir. “Yeşil hastane” uygulamaları, geri dönüşüm ve yeniden kullanım programları ile desteklenmektedir. Ancak bütçe, bilgi eksikliği ve talep sınırlılığı gibi zorluklar sürdürülebilir gıda tedarikini etkilemektedir. Dünya Sağlık Örgütü'nün 2015 değerlendirmesine göre, sadece sağlık kuruluşların %58’i güvenli atık bertaraf sistemine sahiptir(Çatar et al., 2023).

Tıbbi atık yönetiminde, tıbbi atıkların üretiminden bertarafına kadar olan süreç oldukça karmaşık olduğunu ve bu sürecin doğru yönetimi büyük önem arz etmektedir. Hastane atıklarının sınıflandırılması Şekil 1.’de verilmiştir(Ertaş & Güden, 2019).



Şekil 1. Hastane Atıklarının Sınıflandırılması.

Hastanelerdeki farklı birimlerde oluşan atık türlerinin dağılımı, atık yönetiminin her bölüm için özel olarak ele alınması gerektiğini göstermektedir. Hastane birimlerinde atık türleri yüzdesel dağılımında klinik birimlerden ameliyathane, acil servis, yoğun bakım ve hasta servislerinde en fazla atık kâğıt (%60) ve plastik (%30–35) kaynaklıdır. Diyaliz ünitesinde ise plastik atıkların oranı %85'e kadar çıkmakta, bu da plastik atık yönetiminin burada öncelikli olduğunu göstermektedir. Laboratuvarlarda patolojik atık (%25) ve cam atık (%10) oranları dikkat çekerken, eczanelerde cam atıklar (%20) öne çıkmaktadır. Hemşire odalarında ve hasta servislerinde yine kâğıt ve plastik ağırlıklı atıklar bulunmakta; bunun yanı sıra belirli oranda yiyecek ve cam atık da oluşmaktadır. Araştırma birimlerinde kâğıt (%40), patolojik (%30) ve metal (%20) atıklar ön plandadır. Alet biriminde ise atıkların büyük çoğunluğu plastik (%90) ve metalden (%10) oluşmaktadır. Yazı işleri birimi yalnızca kâğıt (%100) atığı üretirken, kafeteryalarda en fazla yiyecek atığı (%30) oluşmakta, kâğıt ve plastik atıklar ise %20 oranındadır(Ertaş & Güden, 2019). 2020 yılında Türkiye'de tıbbi atık miktarı yaklaşık 110 bin tondur. Bu atıkların büyük çoğunluğu, yani yaklaşık 99,4 bin ton sterilize edilerek depolama alanlarında bertaraf edilmiştir. Yakma tesislerinde bertaraf edilen tıbbi atık miktarı ise yaklaşık 10,3 bin tondur. 2020 Yılı Türkiye'deki sağlık kuruluşlarının tıbbi atık miktarı ve bertaraf yöntemleri Şekil 2.'de verilmiştir(TÜİK, 2020). Atık Yönetimi Yönetmeliği (AYY)'ne göre, atık üreticileri her yıl tıbbi atık beyanlarını Çevre, Şehircilik ve İklim Değişikliği Bakanlığı (ÇŞİDB)'nın Entegre Çevre Bilgi Sistemi üzerinden yer alan Atık Beyan Sistemi (TABS) aracılığıyla yapmaktadır. Ülkemizde 2023 yılında ise yaklaşık 17 bin tesis tarafından yapılan beyanlara göre toplam 130,8 bin ton tıbbi atık oluşmuştur(ÇŞİDB, 2023).



Şekil 2. 2020 Yılı Türkiye'deki Sağlık Kuruluşlarının Tıbbi Atık Miktarı ve Bertaraf Yöntemleri.

Şekil 2.'ye göre Türkiye'de tıbbi atık yönetiminin büyük oranda sterilizasyon ve düzenli depolama yöntemine dayandığını göstermekte olup, bu yöntemin uzun vadeli sürdürülebilirliği sınırlı kalabilmektedir. Bu nedenle, çevreye duyarlı yakma sistemlerinin artırılması, atık üretiminin azaltılması ve geri dönüşüm uygulamalarının yaygınlaştırılması sağlık sektöründe çevresel sürdürülebilirlik açısından kritik öneme sahiptir.

2.ARAŞTIRMA VE BULGULAR

Hastane atıklarının bileşiminin belirlenmesi, sıfır atık konseptinin uygulanmasında kritik bir rol oynamaktadır. Plastik ve kâğıt ağırlıklı atık bileşimi, atıkların azaltılması ve geri dönüştürülmesi yoluyla hastane kalitesinin korunması ve iyileştirilmesine yönelik etkili

yönetim stratejilerinin geliştirilmesini mümkün kılmaktadır. Bir sağlık kuruluşunda sıfır atık yönetim sistemi benimsenmiş ve çeşitli çalışmalar yürütülmektedir. Atık potansiyelinin artırılması, yönetim sisteminin etkinliği ve yaygınlaştırılması için personel eğitim programlarının düzenlenmesi gerekmektedir. Ayrıca, hastanenin tüm birimlerinde tıbbi sarf malzemelerinin ihtiyaca uygun kullanımı sağlanmalı ve atıklar özelliklerine göre ayrıştırılarak geri dönüşüm süreçlerine dahil edilmelidir. Bu yaklaşım, çevresel sürdürülebilirliğin desteklenmesi, doğal kaynakların korunması ve sağlık sektörünün ekolojik ayak izinin azaltılması açısından büyük önem taşımaktadır(Öncel et al.).

Hastanelerde sağlık hizmeti sunumu sırasında oluşan tıbbi atıklar, enfeksiyon ve yaralanma riski açısından diğer atık türlerine kıyasla daha yüksek tehlike arz etmektedir. Bu nedenle, tıbbi atıkların uygun şekilde yönetilmesi hem çevresel sürdürülebilirlik hem de sağlık hizmetlerinin güvenliği ve ekonomik verimliliği açısından kritik öneme sahiptir. Yapılan bir çalışmada, bir eğitim ve araştırma hastanesinde 2019 yılı boyunca üretilen tıbbi atık miktarları, Sağlık Bakanlığı'nın Verimlilik Yerinde Değerlendirme Rehberi kapsamında değerlendirilerek, aylık başvuran hasta sayısı, yatan hasta sayısı, yatak sayısı ve diyaliz seans sayısına göre analiz edilmiştir. Çalışmaya göre, hasta başına günlük 0,17 kg, yatan hasta başına 3,48 kg, yatak başına 1,36 kg ve diyaliz seansı başına 1,19 kg tıbbi atık üretildiği tespit edilmiştir. Ayrıca, bu atıkların bertarafı için yapılan harcama 2019 yılında yaklaşık toplam 1,5 milyon TL harcama yapılmıştır. Sonuçlara göre, iyi bir tıbbi atık yönetimi ile atık miktarının ve maliyetlerin azaltılabileceğini, çevresel, ekonomik ve kurumsal sürdürülebilirliğe katkı sağlanabileceğini göstermektedir(Esen & Çalışkan, 2021).

Tıbbi atıkların yönetimi de ciddi maddi boyutlara ulaşmaktadır. 2024 yılı itibarıyla ülkemizde oluşan tıbbi atıkların toplanması, taşınması ve bertaraf edilmesine ilişkin ücretlendirmeye göre Adana ilinde Yüreğir, Sarıçam, Seyhan, Çukurova, Karaisalı, Ceyhan, Karataş, İmamoğlu, Kozan ve Yumurtalık ilçelerinde bulunan sağlık kuruluşlarından alınan tıbbi atıklar için taşıma ücreti 6,55 TL/kg + KDV, bertaraf ücreti 10,04 TL/kg + KDV olmak üzere toplam 16,59 TL/kg + KDV olarak belirlenmiştir. İl merkezine 81 km ve daha uzak mesafede bulunan Aladağ, Feke, Saimbeyli, Tufanbeyli ve Pozantı ilçelerinde ise taşıma ücreti 7,02 TL/kg + KDV, bertaraf ücreti yine 10,04 TL/kg + KDV olmak üzere toplamda 17,06 TL/kg + KDV olarak uygulanmaktadır. Ayda 0–7 kg arası tıbbi atık üreten sağlık kuruluşlarından taşıma hizmeti için 125,64 TL/ay + KDV, bertaraf hizmeti için 10,04 TL/ay + KDV olmak üzere toplam 135,68 TL/ay + KDV, ayda 8–15 kg arası atık üreten kuruluşlar için ise taşıma ücreti 251,32 TL/ay + KDV, bertaraf ücreti 10,04 TL/ay + KDV olmak üzere toplam 261,36 TL/ay + KDV olarak belirlenmiştir. Tıbbi atık üreten kuruluşlardan çıkan patolojik atıkların, özellikleri gereği yakma yöntemiyle bertaraf edilmesi zorunlu olup, Adana iline en yakın patolojik atık yakma tesisi Ankara ilinde bulunduğundan, bu atıkların Ankara'ya gönderilmektedir. Patolojik atıklar için taşıma ücreti 69,41 TL/kg + KDV olarak belirlenmiş olup, bertaraf ücreti ise Ankara Mahalli Çevre Kurulu (MÇK) tarafından ayrıca belirlenmektedir(ÇŞİDB, 2024).

Şanlıurfa bir devlet hastanesinde yapılan bir çalışmada atık üretimi ve sıfır atık yaklaşımı incelenmiştir. 2021 yılına ait veriler doğrultusunda, hastanede plastik ve kâğıt atıkların toplam miktarı 22,76 ton/yıl, tehlikeli atık miktarı 16,55 ton/yıl ve farmasötik, tıbbi ile enfekte atık miktarları ise 458,34 ton/yıl olarak hesaplanmıştır. Kişi başı enfekte atık miktarı ise 2,42 kg/yatak/gün olarak bulunmuştur. Aynı yıl plastik ve kâğıt atıklarda geri dönüşüm miktarı 22,50 ton/yıl düzeyindedir. Hastanede israfın azaltılması amacıyla çeşitli sıfır atık uygulamaları yürütülmekte olup, bu örnek üzerinden kentteki diğer sağlık kuruluşları için sıfır atık projeksiyonu yapılabileceğini önermektedir.

Hastanelerdeki faaliyetlerden kaynaklanan atık oluşumunu ölçen herhangi bir özel yöntem bulunmamaktadır. Genellikle atık kaynağı mutfak ve mutfak dışı kaynaklar olarak ayrılarak işlem yapılmaktadır. Mevcut hastanedeki toplam günlük atık oranını ve atığın özelliklerini belirlemek amacıyla her yatak başına düşen atık ağırlığının hesaplanması için Denklem1 kullanılır(Öncel et al.).

$$G_A = (T_{TA} + T_{MA})/H_G \qquad \text{Denklem 1}$$

G_A=Günlük Atık oranı(kg/yatak/gün-birim)

T_{TA}=Toplam Tıbbi atık(kg/gün-birim)

T_{MA}=Toplam Mutfak Atığı(kg/gün-birim)

H_G=Geceleyen Hasta Sayısı

Sürdürülebilirlik kavramı 1990'larda inşaat sektöründe ortaya çıkmış ve yeşil yapılar olarak gelişmiştir. Yeşil yapılar; çevreye zarar vermeyen, enerji ve suyu etkin kullanan, daha az malzeme tüketen ve sağlıklı iç ortam sağlayan yapılar olarak tanımlanır. 20. yüzyıl sonunda yapıların toplam malzeme, su ve enerji tüketimindeki yüksek payı, yeşil yapıların önemini artırmıştır. Yeşil yapılar, aşırı kaynak kullanımına ve çevre kirliliğine çözümler sunarken, ekonomik fırsatlar sağlamakta ve insan sağlığı ile verimliliğini desteklemektedir. Yeşil yapıların çevresel performansını değerlendirmek amacıyla çeşitli sertifikalandırma sistemleri geliştirilmiştir. İlk sistem İngiltere'de Building Research Establishment's Environmental Assessment Method (BREEAM- Yapı Araştırma Kurumu Çevresel Değerlendirme Yöntemi) olarak ortaya çıkmış, 1998'de ABD'de Leadership in Environmental and Energy Design (LEED- Çevre ve Enerji Tasarımında Liderlik), Avustralya'daki GREENSTAR gibi birçok sistem ortaya çıkmıştır. Bu sistemlerde enerji ve su verimliliği, iç ortam kalitesi ve yenilikçi malzeme kullanımı gibi kriterler puanlanarak yapılar değerlendirilmektedir(Çilhoroz & Işık, 2018).

Artan nüfus ve doğal kaynak kullanımı çevre sorunlarını ortaya çıkarmış, bu da yeşil yapı ve yeşil hastane kavramlarını doğurmuştur. Ankara'daki hastanelerde yapılan çalışmada, yeşil hastane kriterlerine uygunluk genel olarak %72 civarında bulunmuştur. Hastaneler su yönetimi ve sürdürülebilirlikte başarılı olurken, enerji yönetimi ve malzeme seçiminde eksiklikleri bulunmaktadır. Hastanelerde en çok üretilen atıklar yaklaşık bitkisel atık yağlar 6 bin lt, evsel atıklar 420 t ve 106 t tıbbi atıklardır. En az üretilen atık ise nükleer tıp atığı yaklaşık 6 t olarak belirlenmiştir. Kamu hastanelerinde en çok bitkisel atık yağ yaklaşık 11 bin lt, en az nükleer tıp atığı yaklaşık 10 t üretilirken, özel hastanelerde en çok bitkisel atık yağ yaklaşık 750 lt, radyoloji atık suyu ise hiç üretilmemiştir(Çilhoroz & Işık, 2018).

Tıbbi atıklar, insan sağlığı açısından diğer atıklara göre daha yüksek risk taşımakta ve son yıllarda miktarları artmaktadır. Bu atıkların ayrıştırılması, toplanması ve depolanması maliyetli olduğu için, ekonomik yükün azaltılması ve atıkların kaynağında azaltılması büyük önem taşır. Başarılı bir tıbbi atık yönetimi için iyi bir planlama ve yönetim anlayışı gereklidir. Ayrıca, Birleşmiş Milletler gibi uluslararası platformlarda tıbbi atıkların kaynağında engellenmesi veya azaltılması, mümkün olduğunda geri dönüşümünün sağlanması ve atıkların güvenli bir ortamda işlenip bertaraf edilmesi gibi tedbirler önerilmektedir.

Tıbbi atık minimizasyonu, atık yönetiminde öncelikli hedef olarak atık oluşumunun engellenmesini veya en aza indirilmesini amaçlamaktadır. Bu süreçte "Tıbbi Atıkların Oluşumu Sırasındaki Minimizasyon" aşaması, uzun ömürlü ve tek kullanımlık malzemelerin azaltılmasıyla başlar. "Geri Dönüşüm" başlığı altında, satın alma sürecinde geri dönüştürülebilir malzemelerin tercih edilmesi önerilir. "Karar Alma Süreci'nde ise kimyasal

malzemeler için Malzeme Güvenlik Bilgi Formları talep edilerek daha az tehlikeli ürünlerin seçilmesi hedeflenir. Ayrıca, "Üretimin Planlanması" aşamasında atıkların doğru tanımlanması ve tasnifi için ekipman ve eğitim sağlanması önem taşır. Tüm bu adımlar, atıkların doğru sınıflandırılması ve gereksiz tıbbi atık oluşumunun önlenmesiyle atık miktarının ciddi oranda azaltılmasını sağlamaktadır.

Kaynakta azaltımın temel amacı, malzeme üretimini kontrol altına alarak hem atık minimizasyonu sağlamak hem de maliyetleri düşürmektir. Bu kapsamda tüm hastane personelinin eğitimleri, atık azaltmaya yönelik sistemlerinin geliştirilmesi ve daha az tehlikeli maddelerin kullanılması önemli yöntemler arasında yer almaktadır. Ayırma işlemi ise atıkların cinslerine göre ayrı toplanmasını sağlayarak atık miktarının ve hacminin azalmasına katkı sağlamaktadır. Bu süreçte atık tipi, yeniden kullanım ve geri dönüşüm durumu dikkate alınmalı, tüm sağlık çalışanları ve üreticiler sürece dahil edilmelidir. Özellikle tıbbi atıkların ayrıştırılmasında, iğneler, kanla kontamine malzemeler, cerrahi atıklar ve insan ile hayvan kaynaklı atıklar titizlikle belirlenip ayrıştırılmalıdır. Geri dönüşüm ve yeniden kullanımda ise, cerrahi aletler başta olmak üzere uygun malzemeler sterilize edilerek tekrar kullanılır; sterilizasyonun doğru yapılması enfeksiyon riskini önler. Ayrıca, tehlikesiz ambalaj ve kaplar ile diyaliz suyu kapları gibi malzemeler de geri dönüşüm tesislerinde işlenmektedir.

Hastanede oluşan tıbbi atıkların bertaraf edilmesinin temel amacı, atıkların zararlı etkilerine önlem alarak ve çevre sağlığını koruyarak tehlikesiz hale getirmektir. Bertaraf yöntemleri, atığın türüne göre farklılık göstermekte olup, çeşitli kimyasal, termal teknikler uygulanmaktadır. Kimyasal bertaraf yönteminde kesici aletlerde O_3, NaOCl gibi etken maddeler kullanılarak tıbbi atıkların dezenfeksiyonu sağlanmaktadır. Termal bertaraf yöntemleri ise düşük ve yüksek ısıl işlemler olarak uygulanmakta; düşük ısıl işlemde otoklavlama ile buhar kullanılırken, yüksek ısıl işlemde yakma işlemi yapılmaktadır. Mekanik işlemler atıkların sıkıştırılması ve parçalanması gibi fiziksel yöntemlerle atık hacmini azaltmakta, ancak patojenleri yok etmemektedir. Işınlama yöntemleri elektromanyetik radyasyon kullanarak patojenleri imha eder ancak yüksek risk taşımaktadır. Biyolojik süreçte organik atıkların ayrıştırılması için sindirim enzimleri ve kompostlama yöntemleri uygulanmaktadır. Yakma ise yüksek sıcaklıkta (1000-2000°C) gerçekleşen ve kullanım süresi dolmuş tehlikeli atıkların oksidasyon yoluyla bertaraf edilmesidir; bu süreç dikkatle denetlenmelidir çünkü zararlı kimyasal reaksiyonlar oluşabilmektedir(Ertaş & Güden, 2019). Şekil 3.'te Atık yönetimi hiyerarşisi verilmiştir(Tripathi et al., 2022).



Şekil 3. Atık Yönetimi Hiyerarşisi.

Atık yönetiminde çevresel etkileri azaltmak ve kaynak verimliliğini artırmak amacıyla 3-R (Azaltma, Yeniden Kullanım ve Geri Dönüşüm) ilkelerine dayalı atık yönetimi hiyerarşine göre, atık oluşumunu önleme ve atıkların çevreye zarar vermeyecek şekilde yönetilmesini sağlama hedefini taşımaktadır. Azaltma, hiyerarşinin en üstünde yer alır ve atığın kaynağında oluşmasının engellenmesini, yeniden kullanım ömrü tamamlanmamış ürünlerin tekrar değerlendirilmesini, geri dönüşüm ise atığın işlenerek tekrar ham madde veya ürün olarak ekonomiye kazandırılmasını içermektedir. Bu sıralama, çevresel kazancın en fazla olduğu uygulamadan en az etkili olana doğru bir önceliklendirme sağlamaktadır(Tripathi et al., 2022).

Yapılan bir çalışmaya göre, hastane atıklarının yönetiminde yerinde buhar sterilizasyonu ile gazlaştırma teknolojisinin kullanımı, çevresel sürdürülebilirlik açısından etkili bir alternatif sunmaktadır. Avustralya hastanelerinde gerçekleştirilen değerlendirmede, hastane atıklarının büyük kısmını genel atıkların (%84,8), küçük bir kısmını ise klinik atıkların (%6,9) oluşturduğu belirlenmiştir. Genel atıkların çoğunluğu plastik (%74,5) ve kâğıt/karton (%13,4) gibi geri dönüştürülebilir malzemelerden oluşmaktadır. Gazlaştırma yöntemiyle bu atıkların işlenmesinin, çöp sahalarına gönderilen atık miktarını ve atık taşımacılığı ile yakma işlemlerinden kaynaklanan emisyonları %95,9 oranında azaltabileceği ortaya konmuştur. Ayrıca bu yöntem, çöp sahalarının kullanım ömrünü uzatmakta ve geri dönüşüm potansiyelini artırmaktadır. 2019/2020 verilerine göre Avustralya hastanelerinde yılda yaklaşık 230.717 ton atık üretildiği göz önünde bulundurulduğunda, bu çalışmada önerilen sistemin uygulanabilirliği ve çevresel faydaları büyük önem taşımaktadır. Bu bulgular, hastane atık yönetiminde daha döngüsel ve çevre dostu yaklaşımların benimsenmesine katkı sağlayabilir(Harris & McCabe, 2024). Tıbbi atıklar sağlık hizmetleri sırasında ortaya çıkan ve tehlikeli ile tehlikesiz olarak sınıflandırılan çeşitli materyalleri içermektedir. Bangladeş'in Dakka şehrindeki iki hastanesinde yapılan çalışmaya göre, sağlık çalışanlarının tıbbi atık yönetimi konusunda çalışanların eğitimi ve bilinçlendirilmesi gerektiğini belirtmişlerdir. Toplam atığın yaklaşık %15'inin tehlikeli olduğu ve bu atıkların uygun şekilde bertaraf edilmemesi halinde hem iş sağlığı ve güvenliği

açısından ciddi riskler oluşturduğu hem de çevre kirliliğine yol açtığı vurgulanmıştır. Özellikle sağlık çalışanlarının, kontamine iğne batması gibi yaralanmalar nedeniyle kan yoluyla bulaşan patojenlere maruz kalma riski oldukça yüksek olduğunu belirtmişlerdir. Bu durum, tıbbi atıkların doğru yönetiminin halk sağlığı ve çevre güvenliği açısından kritik önem taşıdığını göstermektedir(Islam et al., 2025).

3.SONUÇ

Hastaneler, teknolojik gelişmeler ve artan sağlık ihtiyaçları nedeniyle giderek daha fazla başvuru alan, yoğun kullanılan sağlık kurumlarıdır. Bu hizmet sürecinde çeşitli türlerde atıklar oluşur. Artan tıbbi faaliyetlere paralel olarak bu atıkların miktarı ve çeşitliliği de sürekli artmaktadır. Hastanelerde oluşan atıklar; evsel (genel) atıklar, tıbbi/patolojik/enfekte atıklar, kimyasal atıklar ve radyoaktif atıklar olmak üzere dört ana gruba ayrılır. Dünya Sağlık Örgütü'ne göre bu atıkların yaklaşık %80'i evsel, %15'i enfekte-patolojik, %1'i kesici-delici ve %4'ü farmasötik atıklardır.

Türkiye'de hastaneler, "Tıbbi Atıkların Kontrolü Yönetmeliği (TAKY)" çerçevesinde atıkları kaynağında ayrıştırmak, toplamak, depolamak ve azaltmakla yükümlüdür. Bu sürecin etkili bir şekilde yürütülebilmesi için sağlık çalışanlarının bilgi ve tutumu büyük önem taşımaktadır. TAKY ile tıbbi atıkların kontrollü bir şekilde toplanması, taşınması ve bertarafı yasal zorunluluk haline gelmiştir. Bu sürecin etkin yürütülebilmesi için, atıkların kaynağında ayrıştırılması ve kurumsal düzeyde atık yönetimi kültürünün geliştirilmesi gerekmektedir(İncesu & Evirgen, 2017).

Bangalore şehrindeki diş hekimliği eğitim hastanelerinde yapılan çalışmaya göre, artan kentleşmenin sağlık sektöründe yol açtığı olumlu gelişmelerin yanında, biyomedikal atıkların uygunsuz yönetimi çevresel ve halk sağlığı açısından ciddi tehditler oluşturmaktadır. Özellikle hastane personelinin atık yönetimi konusunda eğitimsiz olması, sorunun derinleşmesine neden olmaktadır. Personelin hastane atık yönetimi konusunda bir günlük eğitim programı uygulanmıştır. Eğitimin ardından katılımcıların bilgi düzeylerinde anlamlı iyileşmeler kaydedilmiştir. Eğitim programlarının hastane atık yönetiminde bilgi ve farkındalığı artırmada etkili olduğunu göstermektedir. Ayrıca, uygun atık yönetimi uygulamalarının yaygınlaştırılabilmesi için sağlık kuruluşlarında eğitimlerin düzenli ve sistematik olarak sunulmasının gerekliliği vurgulanmaktadır(Rudraswamy, 2014). Endonezya'daki hastanelerde yapılan çalışmaya göre, sıvı tıbbi atık yönetimi konusunda uyum düzeyini etkileyen faktörler net olarak belirlenememektedir ve bu alanda kanıta dayalı veriye ihtiyaç duyulmaktadır. 2017–2023 yılları arasındaki literatür taramasıyla yapılan bu sistematik inceleme, hastanelerde tehlikeli atık yönetimine yönelik mevcut uygulamaların değerlendirilmesini ve yönetmeliklere uyumu etkileyen belirleyicilerin haritalandırılmasını amaçlamıştır. Çalışma kapsamında incelenen makalelerden biri yönetmeliklere uyumu, diğeri ise atık yönetiminin denetimini ele almakta; ancak her iki çalışma da denetim süreçlerini yeterince ayrıntılı olarak açıklamamaktadır. Bu durum, hastane atık yönetimi süreçlerinin etkinliğini değerlendirmek ve sonuçlarını iyileştirmek için denetim mekanizmalarının güçlendirilmesi gerektiğine işaret etmektedir. Araştırma sonuçları, yönergelere uyumun sadece yasal bir zorunluluk değil, aynı zamanda halk sağlığı ve çevreyi koruma açısından da bir alışkanlık haline getirilmesi gerektiğini vurgulamaktadır. Etkin ve sürekli iyileştirme odaklı bir denetim sistemi, hastanelerdeki atık yönetim süreçlerinin sürdürülebilirliğini sağlamada kritik bir rol oynamaktadır(Kaban et al., 2025).

Turgutlu Devlet Hastanesi'nde yapılan bir çalışmaya göre, sağlık tesislerinde önemli bir sorun olarak ortaya çıkan konulardan biri tıbbi atıkların etkin yönetimidir. Sağlık kuruluşlarında oluşan atıkların büyük bir kısmını tıbbi atıklar oluşturmaktadır. Enfeksiyon kontrol ve tesis güvenliği komitelerinin aylık analizlerinde atık miktarında belirgin bir artış gözlemlenmiş, bu durum etkili bir atık yönetim planının gerekliliğini ortaya koymuştur. Bu bağlamda gerçekleştirilen çalışmada, Turgutlu İlçe Devlet Hastanesi'nde görev yapan sağlık personelinin tıbbi atık yönetimi konusundaki bilgi düzeylerini, algılarını ve uygulama yeterliliklerini değerlendirmek; elde edilen sonuçlar doğrultusunda eğitim programları oluşturmak ve maliyet etkin bir atık yönetim planı geliştirmek amaçlanmıştır(Yazgan et al., 2014). İzmir Urla Devlet Hastanesi'nde yapılan bir çalışmada, görev yapan 170 sağlık çalışanının tıbbi atıkların toplanması, taşınması, depolanması ve işleme tesisine güvenli ulaştırılması konusundaki bilgi düzeyleri incelenmiştir. Hastane çalışanlarının tıbbi atıklar konusundaki doğru bilgi oranı ortalama %86 olarak bulunmuş olup, sağlık çalışanlarına tıbbi atık yönetimi konusunda düzenli eğitim verilmesi ve belirli aralıklarla denetim yapılmasının, atık yönetimi farkındalığını artırarak uygulamaların etkinliğini yükselteceğini vurgulamaktadır(Şahin & Yiğit, 2024). Nevşehir ve Kayseri illerinde yapılan bir çalışmada, en az 20 yatak kapasitesine sahip dört özel hastane araştırılmıştır. Bu hastanelerde toplam yaklaşık 1338 personel çalışmakta olup, günlük tıbbi atık miktarı incelenmiştir. Araştırma sonuçlarına göre, iki hastanede günlük ortalama tıbbi atık miktarı 60 kg civarında iken, diğer iki hastanede yaklaşık 135 kg olarak belirlenmiştir. Bu veriler, hastanelerdeki tıbbi atık üretiminin önemli seviyelerde olduğunu göstermekte ve tıbbi atık yönetim uygulamalarının yeterince etkin ve başarılı olmadığını ortaya koymuştur. Bu sonuçlar, sağlık kurumlarında atık yönetiminin geliştirilmesi ve iyileştirilmesi gerekliliğini göstermektedir(Cingöz & Tinni, 2020).

Yeşil binalar, doğa dostu teknolojileri bünyesinde barındırarak israfı azaltmakta, ısıtma-soğutma maliyetlerini düşürerek sağlıklı çevre ortamları sağlamaktadır. Bu binaların bakımından da maliyet ve zaman tasarrufu sağlanmakta, hava kalitesini iyileştirmektedir. Ayrıca, yeşil bina standartlarına yapılan yatırımlar uzun vadede mülk değerini artırmakta, enerji verimliliği sağlamakta ve enerji yasalarına uyumu teşvik etmektedir. Amerika'da yerel ve federal düzeyde yeşil bina yapımına yönelik vergi teşvikleri de bulunmaktadır. Yeşil bina uygulamaları, yeni inşaatlar, yenilemeler, okul binaları, kentsel dönüşüm projeleri ve özellikle sağlık kuruluşlarında yaygınlaşmaktadır. Yeşil hastane" kavramı, çevre dostu yerleşim seçiminden sürdürülebilir tasarımlara, doğa dostu malzeme kullanımından inşaat ve hizmet süreçlerinde çevre duyarlılığına kadar çeşitli çevresel kriterleri karşılayan sağlık tesislerini ifade etmektedir. Bu hastaneler, geri dönüşüm uygulamalarıyla atık miktarını azaltmakta ve çevreye daha temiz hava sağlamaktadır. Yeşil hastanelerde uygulanan çevresel ve sağlık odaklı prensiplerin, tesis planlama, tasarım, inşa ve bakım süreçlerine entegre edilmesi maddi ve manevi birçok fayda sunmaktadır. Yapılan araştırmalar, yeşil hastanelerde yatan hastaların duygusal açıdan daha iyi durumda olduğunu, daha az ağrı kesici kullandığını ve daha kısa sürede taburcu edildiğini göstermektedir. Bu nedenle, sağlık kurumları için yeşil stratejilerin geliştirilmesi ve uygulanması önem taşımaktadır(Terekli et al., 2013).

Ermenek Devlet Hastanesi'nde yapılan bir araştırmada sıfır atık yönetimi uygulamaları ile toplanan tıbbi atıkların yıllara, aylara, birimlere, yatan hasta sayısına, maliyete ve atık türlerine göre dağılımı incelenmiştir. 2013–2024 yılları arasında toplam yaklaşık 139 bin kg tıbbi atık toplanmış; en fazla atık 2023 yılında yaklaşık 19 bin kg, en az atık ise 2013 yılında yaklaşık 3 bin kg olarak tespit edilmiştir. 2017–2023 yılları arasında birim bazında en fazla tıbbi atık yaklaşık 21 bin kg ile diyaliz biriminde, en az atık ise 133 kg ile palyatif ünitede oluşmuştur. 2014–2024 yılları arasında hastanede yaklaşık 29 bin hasta yatarak tedavi görmüş, hasta başına düşen en yüksek tıbbi atık oranı ise 2021 yılında yaklaşık 12 kg olarak hesaplanmıştır. 2022–

2024 yılları arasında toplanan atıkların toplam maliyeti yaklaşık 560 bin TL olarak gerçekleşmiştir(Çataltaş, 2024).

Hastane atıkların yönetimi için Dünya Sağlık Örgütü'ne (WHO) göre olması gereken önlemlerden biri atıklar hasta odalarından başlayarak toplanmalıdır. Evsel atıklar ile tıbbi atıklar asla karıştırılmamalıdır. Hastane atıkları uygun atık taşıma araçlarıyla taşınmalı, bu araçların düzenli dezenfekte edilmesi sağlanmalıdır. Tehlikeli atıklar, uzman firmalarca bertaraf edilmelidir. Radyoaktif ve kimyasal atıklar için güvenli depolama alanları oluşturulmalıdır. Hastanede atık yönetimi planları, sağlık kuruluşlarının kuruluş aşamasında tamamlanmalıdır. Hastane atık miktarları, hasta sayısına göre planlanmalı, atıklar türlerine göre ayrıştırılmalıdır. Büyük hastaneler kendi bertaraf yöntemlerini uygulayabilirken, küçük sağlık kuruluşları için ortak bertarafı sağlanmalıdır. Hastanelerin atık yönetiminde kullanılan araç ve gereçlerin, mevzuat hükümlerine uygun olması gerekmektedir. Hastane atık yönetiminde amaç, sağlık ve çevre risklerini en aza indirmektir(Ertaş & Güden, 2019).

Tıbbi atıklar, hastane ve laboratuvarlarda oluşan enfeksiyöz, kimyasal ve radyoaktif atıklardır. Sağlık kuruluşlarındaki atıkların çoğu (%75-80) evsel, sadece %5-10'u enfeksiyözdür. Atıkların kaynağında ayrılması önemlidir çünkü enfeksiyöz atıkların bertaraf maliyeti evsel atıklardan daha yüksektir. Sağlık kurumlarında tıbbi atıkların doğru yönetimi için etkili bir atık yönetimi planı ve hastane personeline düzenli eğitimler gereklidir.

Etkili hastane atık yönetiminin önemli adımlarından biri atıkların azaltılmasıdır. Geri kazanılabilir atıklar için uygun poşet eksikliği tespit edilerek çalışmalar başlatılmalıdır. Atıkların doğru kovaya atılması için sağlık personeline bilgilendirici yazılar asılmış ve eğitimler planlanmalıdır. Hastanelerde sürdürülebilir atık yönetimi için periyodik eğitimler ve yeterli bütçe gereklidir(İncesu & Evirgen, 2017).

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İlgi : 01.10.2025 tarihli dilekçeniz.

İlgi sayılı yazınıza istinaden; 27-29 Kasım 2025 tarihleri arasında Kıbrıs'ta düzenlenecek olan "ISPEC 18. Uluslararası Mühendislik ve Fen Bilimleri Kongresi'ne kongre başkanı olarak katılım sağlama isteğiniz; Fakültemiz Dekanlığınca uygun görülmüştür.

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