Inflammopharmacology
https://doi.org/10.1007/s10787-026-02252-z

REVIEW

Nature meets immunity: curcumin's role in modulating neutrophil extracellular traps

Amirhossein Sahebkar[1,2,3] · Elaheh Mirhadi[4] · Tannaz Jamialahmadi[5] · Sercan Karav[6] · Prashant Kesharwani[7]

Received: 15 September 2025 / Accepted: 13 April 2026
© The Author(s), under exclusive licence to Springer Nature Switzerland AG 2026

Abstract

NETosis represents a distinct type of neutrophil activation, marked by the discharge of neutrophil extracellular traps (NETs) network-like formations mainly consisting of decondensed chromatin interspersed with antimicrobial proteins sourced from neutrophil granules and cytoplasmic components. Although NETosis are essential for host defense, their overproduction is associated with tissue injury, vascular blockage, and prolonged inflammation, which plays a significant role in the development of numerous inflammatory and autoimmune diseases. Curcumin, a naturally occurring polyphenol known for its strong anti-inflammatory and antioxidant effects, has been recognized as a potential modulator of NETosis. This review examines the molecular mechanisms through which curcumin reduces NET formation, focusing on the regulation of oxidative stress-responsive pathways, inflammatory signaling pathways such as MEK/ERK, and the activation of the NLRP3 inflammasome. Additionally, it emphasizes curcumin's therapeutic potential in conditions characterized by abnormal NETs activity.

✉ Amirhossein Sahebkar
amir_saheb2000@yahoo.com

✉ Prashant Kesharwani
prashantdops@gmail.com

1 Biotechnology Research Center, Pharmaceutical Technology Institute, Mashhad University of Medical Sciences, Mashhad, Iran

2 Centre for Research Impact and Outcome, Chitkara College of Pharmacy, Chitkara University, Rajpura, Punjab 140401, India

3 Applied Biomedical Research Center, Basic Sciences Research Institute, Mashhad University of Medical Sciences, Mashhad, Iran

4 School of Pharmacy, Mashhad University of Medical Sciences, Mashhad, Iran

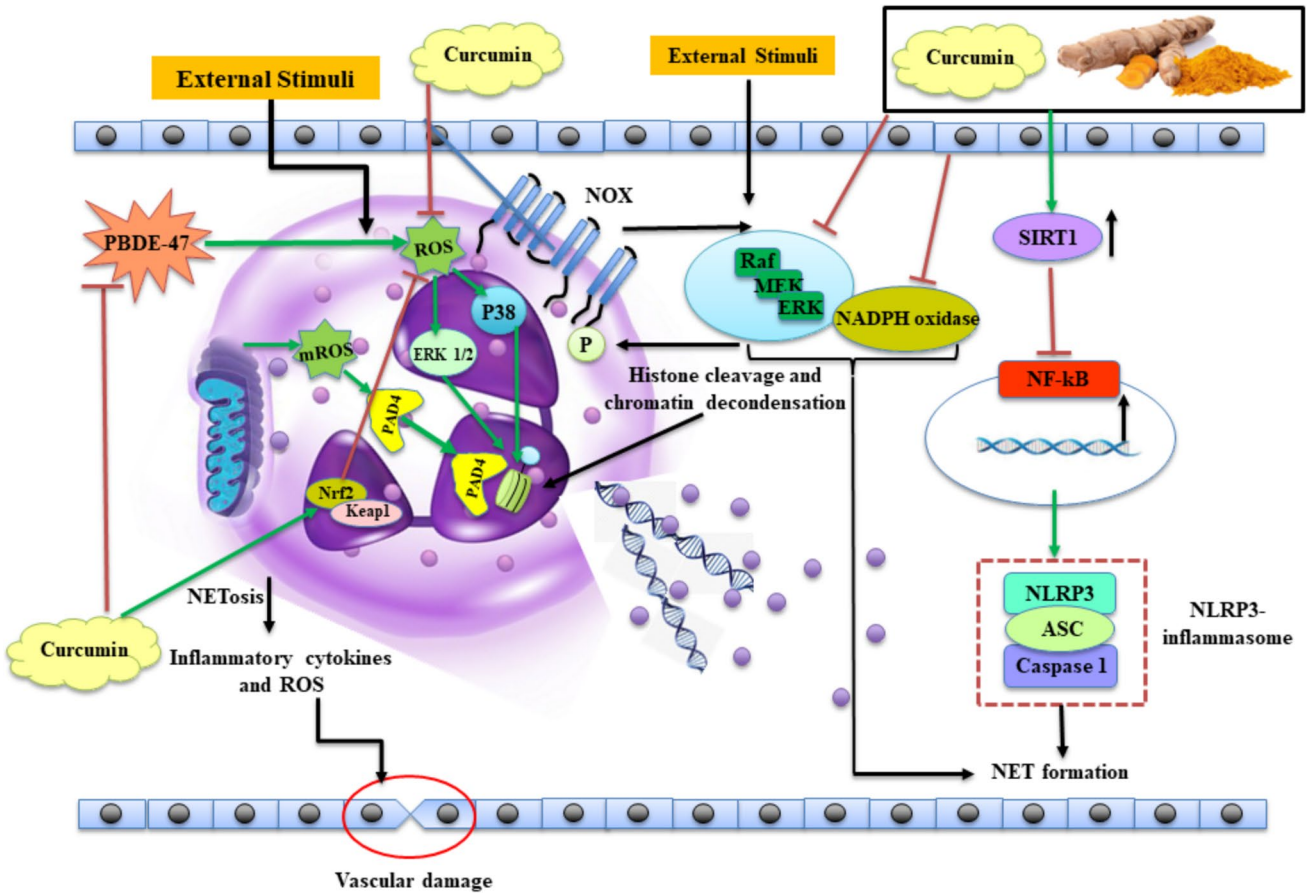
5 Pharmaceutical Research Center, Pharmaceutical Technology Institute, Mashhad University of Medical Sciences, Mashhad, Iran

6 Department of Molecular Biology and Genetics, Canakkale Onsekiz Mart University, 17100 Canakkale, Turkey

7 Next-Generation Translational Nanomedicine Laboratory, Department of Pharmaceutical Sciences, Dr. Harisingh Gour Vishwavidyalaya (A Central University), Sagar, Madhya Pradesh 470003, India

Published online: 23 May 2026

Graphical abstract



Keywords Neutrophil extracellular traps (NETs) · NETosis · Curcumin · Natural compounds · Therapeutic potential · Inflammation · Oxidative stress · Immunomodulation

Introduction

As an initial line of defense against infections, neutrophil extracellular traps (NETs) are an intriguing feature of the immune response (Brinkmann et al. 2004). Neutrophils extrude these web-like structures, which are made of DNA and antimicrobial proteins, in a process called NETosis. In addition to neutrophils, the release of extracellular DNA upon stimulation has also been documented in basophils, eosinophils, macrophages and mast cells (Morshed et al. 2014). Although NETs are crucial for capturing and eliminating microorganisms, an overabundance of them can have serious pathogenic effects and contribute to a number of illnesses, such as chronic inflammatory diseases, cardiovascular diseases, and autoimmune disorders (Thakur et al. 2021). The release of extracellular traps was originally characterized as a programmed cell death mechanism apart from both apoptosis and necrosis. It is believed that this process can take place without cell lysis, and considered as a phenomenon referred to as vital NETosis (Thiam et al. 2020). This paper provides a brief overview of the potential therapeutic avenues that curcumin may present in addressing NET-mediated pathogenesis.

An increasing number of both natural and synthetic compounds has been recognized as possible modulators of the formation of NETs (Mutua and Gershwin 2021). These approaches aim at various phases of NETosis, which encompass NET degradation (for instance, DNase I), inhibition of chromatin decondensation (such as PAD4 inhibitors like Cl-amidine), suppression of the oxidative burst (for example, antioxidants), and modulation of inflammatory signaling pathways (Yadav et al. 2023). Although numerous synthetic inhibitors exhibit significant specificity for particular molecular targets, their application in clinical settings may be constrained by safety issues or limited therapeutic windows (Zambrano et al. 2025).

Natural compounds such as flavonoids and polyphenols, exhibiting anti-inflammatory and antioxidant characteristics

(Askarizadeh et al. 2025), thereby serving as potential modulators of NETosis. Among these, curcumin stands out due to its extensive regulatory influence on various signaling pathways involved in NETosis, which encompass oxidative stress-responsive, inflammatory, and inflammasome-related processes. In contrast to inhibitors that target a single pathway, curcumin demonstrates pleiotropic effects that could be beneficial in intricate inflammatory settings marked by redundant and overlapping signaling mechanisms (Askarizadeh et al. 2025). Nonetheless, the therapeutic potential of curcumin should be evaluated in conjunction with its limitations, especially regarding bioavailability and the feasibility of translation (El-Saadony et al. 2025; Adeleye et al. 2025). Placing curcumin within the wider context of NET-targeting strategies highlights the necessity for comparative and combinatorial methods to effectively influence pathological NET formation.

The dual role of NETs and NETosis

NETs serve an essential protective function in innate immunity by capturing and neutralizing invading pathogens. Nevertheless, uncontrolled NET formation often termed NETosis can have harmful consequences and play a role in the development of diseases (Shahzad et al. 2025). Excessive or ongoing production of NETs has been linked to tissue damage and chronic inflammation in autoimmune conditions like rheumatoid arthritis and systemic lupus erythematosus. Furthermore, in the context of cardiovascular diseases, a disruption in the balance of NET homeostasis is correlated with thrombosis, endothelial dysfunction, and vascular injury (Ma et al. 2025).

NETs participate in both sterile inflammation and infectious responses, and their pathological impact largely depends on the magnitude and context of their formation. Overabundant NET accumulation promotes tissue injury, vascular occlusion, and chronic inflammatory reactions, thereby exacerbating the progression of various pathological conditions (Block et al. 2022). NETosis can be triggered by diverse stimuli, including microbial products and pro-inflammatory cytokines, and is characterized by a distinct form of neutrophil activation that differs from apoptosis and necrosis. During this process, decondensed chromatin decorated with granular proteins is released into the extracellular space, forming NET structures that can amplify inflammatory signaling (Jia et al. 2025).

Crucially, NETs play a dual role in the pathophysiology of diseases. On one side, components derived from NETs can serve as autoantigens, which stimulate autoimmune responses; conversely, aggregated NET complexes may act as inflammatory intermediates by influencing the activity of pro-inflammatory chemokines and cytokines. These effects, which depend on the context, underscore the importance of tightly regulated NET formation to uphold immune homeostasis and avert pathological inflammation (Fousert et al. 2020).

Molecular signaling pathways involved in NETosis and their therapeutic modulation by curcumin

Growing evidence underscores the role of abnormal or excessive NET formation as a significant contributor to chronic inflammation, tissue damage, and autoimmune conditions, such as systemic lupus erythematosus (SLE), autoinflammatory diseases, and renal inflammatory disorders (Zeng et al. 2025; Kaplan 2024; Barnado et al. 2016; Wigerblad and Kaplan 2023). Several interconnected signaling pathways have been identified as central regulators of NETosis, providing attractive targets for therapeutic intervention.

ROS-dependent signaling in NET formation

The generation of reactive oxygen species (ROS), mainly facilitated by NADPH oxidase (NOX2), is regarded as a crucial upstream event in classical NETosis (Almyroudis et al. 2013; Vorobjeva and Chernyak 2020). ROS function as secondary messengers and are involved in a wide range of diseases and pathological states (Ansari et al. 2025; Song and Zou 2015). ROS can trigger chromatin decondensation and enhance the subsequent activation of NET-associated enzymes (Liu et al. 2022; Zambrano et al. 2025). Abnormal ROS production has been closely associated with prolonged NET release in autoimmune and autoinflammatory disorders, where oxidative stress exacerbates inflammatory signaling pathways (Wójcik et al. 2021; Yan et al. 2023). Curcumin, a well-characterized polyphenolic antioxidant, has demonstrated to markedly suppress intracellular ROS generation through both direct free radical scavenging and inhibition of NOX2 activity (Derochette et al. 2013). By attenuating oxidative stress, curcumin can be effective in disrupting the initiation phase of ROS-dependent NETosis.

PAD4-mediated histone citrullination

Peptidylarginine deiminase 4 (PAD4) is essential for the formation of NETs as it catalyzes the citrullination of histones, which results in the decondensation of chromatin and the rupture of the nuclear envelope (Liu et al. 2021; Kijak-Bońkowska et al. 2025). Elevated PAD4 activity and excessive histone citrullination have been observed in autoimmune diseases such as SLE, where NET-derived citrullinated antigens contribute to autoantibody generation (Ciesielski et al. 2022; Liu and Kaplan 2021). Curcumin has indicated to attenuate PAD4 activity through the regulation

of intracellular calcium balance and the mitigation of oxidative stress, two critical factors required for optimal PAD4 enzymatic function (Bardak et al. 2017). Through this mechanism, curcumin may act as an effective regulator of chromatin decondensation processes associated with NET formation.

MAPK signaling pathways

Mitogen-activated protein kinase (MAPK) pathways, including ERK1/2, p38, and JNK, are key regulators of neutrophil activation and inflammatory responses (Keshari et al. 2013). Activation of these kinases promotes transcriptional and post-translational events that facilitate NET release (Keshari et al. 2013). Enhanced MAPK signaling has been documented in inflammatory and renal diseases associated with pathological NET formation (Wu et al. 2024). Curcumin exerts potent anti-inflammatory activity in neutrophils by regulating multiple intracellular signaling cascades. Notably, curcumin markedly suppresses MAPK pathway activation, particularly the phosphorylation of p38 and JNK, in lipopolysaccharide-stimulated human neutrophils. This inhibitory effect is accompanied by a substantial reduction in the production of key pro-inflammatory cytokines, including TNF-α, IL-6, and IL-8 (Cho et al. 2020). Curcumin has consistently demonstrated inhibitory effects on MAPK phosphorylation across multiple inflammatory models (Shamsnia et al. 2023), thereby dampening neutrophil activation and reducing NET production.

NF-κB–dependent inflammatory signaling

The NF-κB pathway is a central orchestrator of inflammatory gene expression and neutrophil priming. The involvement of NF-κB in the pathophysiology of various diseases and pathological processes signifies the role of this transcription factor as a therapeutic target (Xu et al. 2020; Cheng et al. 2025; Guo et al. 2024; Camandola and Mattson 2007). NF-κB activation enhances the production of pro-inflammatory cytokines and chemokines that facilitate neutrophil recruitment and NET formation, particularly in autoimmune and autoinflammatory diseases (Liu et al. 2017). Curcumin is a potent inhibitor of NF-κB signaling, acting through suppression of IκBα degradation and inhibition of p65 nuclear translocation (Liczbiński et al. 2020). Through this mechanism, curcumin not only can limit NETosis but also disrupts the inflammatory microenvironment that sustains excessive NET formation.

NLRP3 inflammasome and NET-inflammasome crosstalk

Recent studies have revealed a bidirectional crosstalk between NETs and the NLRP3 inflammasome, whereby NET components activate inflammasome signaling, and inflammasome-derived cytokines further promote NET release (Xiong et al. 2025). This vicious cycle is particularly relevant in autoimmune diseases and chronic inflammatory conditions. Curcumin is able to suppress NLRP3 inflammasome assembly and caspase-1 activation, leading to reduced IL-1β and IL-18 production (Hasanzadeh et al. 2020). By targeting this NET-inflammasome axis, curcumin may exert a dual anti-inflammatory effect.

Therapeutic implications

Collectively, these findings underscore NETosis as a multi-step and multi-target process amenable to therapeutic modulation. Unlike single-target inhibitors, curcumin exerts pleiotropic regulatory effects across multiple NET-related signaling pathways, including ROS generation, PAD4 activation, MAPK and NF-κB signaling, and NLRP3 inflammasome activation. This multi-modal mechanism of action supports the emerging concept of targeting NETosis as a therapeutic strategy in inflammatory, autoimmune, and renal diseases (Askarizadeh et al. 2025). The generation of ROS is a crucial initial event in the process of canonical NETosis, functioning as a molecular switch that connects neutrophil activation to the remodeling of chromatin (Azzouz and Palaniyar 2024; Shen et al. 2025). Increased levels of ROS activate NADPH oxidase-dependent signaling pathways and enhance mitochondrial ROS amplification, subsequently initiating downstream pathways such as MAPK activation and PAD4-mediated histone citrullination (Sendtner et al. 2025; Lee and Jose 2021). Curcumin disrupts this mechanism by both directly and indirectly diminishing the accumulation of intracellular ROS. It achieves this by inhibiting the activity of NADPH oxidase and bolstering antioxidant defenses via Nrf2-dependent transcriptional pathways, thereby reinstating redox equilibrium in neutrophils (Cui et al. 2025; Yu et al. 2025). The attenuation of ROS signaling restricts the phosphorylation of MAPK, diminishes the enzymatic activity of PAD4, and inhibits excessive chromatin relaxation. As a result, the redox modulation induced by curcumin interferes with the molecular cascade necessary for the formation of NETs, thereby offering a mechanistic rationale for its inhibitory effects on NETosis.

Disease-specific roles of NETs and therapeutic implications of curcumin-mediated NET inhibition

Growing evidence suggests that NETs play a significant role in the development of various inflammatory and immune-mediated conditions. In order to enhance the understanding of the therapeutic implications of targeting NETosis, the mechanisms associated with NETs can be classified based on the primary categories of diseases (Xuan et al. 2024).

Autoimmune and autoinflammatory diseases

In autoimmune conditions like systemic lupus erythematosus, rheumatoid arthritis, and vasculitis, the overproduction of NETs plays a significant role in causing tissue injury, persistent inflammation, and the exposure of autoantigens (Wigerblad and Kaplan 2023). Components derived from NETs, such as citrullinated histones and DNA–protein complexes, act as strong immunostimulatory signals that enhance the production of autoantibodies and type I interferon responses. The suppression of ROS generation, PAD4 activity, and pro-inflammatory signaling pathways by curcumin may help to restrict abnormal NET formation, consequently decreasing the burden of autoantigens and the amplification of inflammation in autoimmune contexts (Maronek and Gardlik 2022).

Cardiovascular and thromboinflammatory disorders

NETs have become essential mediators in the processes of vascular inflammation, endothelial dysfunction, and thrombosis. In the context of cardiovascular diseases, NETs serve as a framework for the adhesion of platelets and the activation of coagulation factors, thereby facilitating immunothrombosis and contributing to ischemic tissue damage (Szymańska et al. 2025; Kimball et al. 2016; Döring et al. 2017). Curcumin could diminish oxidative stress and inflammatory signaling within neutrophils, which may lead to a reduction in NET-induced thromboinflammatory responses and an enhancement of vascular homeostasis.

Infectious diseases

During an infection, NETs serve a protective function by capturing and neutralizing pathogens; however, an overproduction or dysregulation of NET formation can worsen tissue damage and inflammatory harm. In cases of severe infections and sepsis, the unregulated release of NETs has been associated with organ dysfunction (Liao et al. 2025; Islam and Takeyama 2023; Pignataro et al. 2025). The modulation of NETosis by curcumin may assist in reestablishing a balanced immune response by curtailing excessive NET formation while maintaining antimicrobial defense.

Cancer

Recent research suggests that NETs play a significant role in tumor advancement, metastasis, and thrombosis related to cancer by altering the tumor microenvironment and aiding in immune evasion. NET constituents have been demonstrated to enhance the adhesion and migration of tumor cells (Li et al. 2025; Morawiec et al. 2025). Curcumin and its analogs are well-known for its anti-tumor properties, which have been demonstrated by various lines of evidence (Hamzehzadeh et al. 2018; Momtazi-Borojeni and Sahebkar 2016; Shafabakhsh et al. 2019; Wang et al. 2023). Due to its anti-inflammatory and antioxidant characteristics, curcumin may disrupt NET-mediated protumorigenic activities, indicating its possible adjunctive function in cancer treatment.

Collectively, these insights specific to various diseases underscore NETosis as a common pathological mechanism present in different clinical scenarios. Curcumin, by influencing several signaling pathways that play a role in NET formation, serves as a versatile modulator with possible therapeutic implications across inflammatory, autoimmune, cardiovascular, infectious, and oncological conditions. However, additional experimental and clinical studies focused on specific diseases are necessary to confirm these effects and establish therapeutic strategies tailored to particular contexts.

Curcumin: a potential NET modulator

Curcumin has drawn interest due to its various pharmacological activities including anti-inflammatory and antioxidant features (Mirhadi et al. 2024; Heidari et al. 2023; Panahi et al. 2014; Saberi-Karimian et al. 2020; Sadeghi et al. 2023). Curcumin may have therapeutic promise in treating diseases marked by excessive NET activity, according to emerging evidence that suggests it may alter NET development and NETosis (Tao et al. 2026; Ye et al. 2021).

Curcumin may could target NE by reducing NE-induced tumor cell proliferation as it has shown inhibition of neutrophil elastase-induced proliferation in human lung adenocarcinoma A549 cells (Xu et al. 2012). It has been able to reduce NETosis-driven tissue damage in hepatic ischemia–reperfusion injury in mice as well (Xu et al. 2012). Curcumin relieves this damage and reduce the formation of NETs (Zhu et al. 2023). (Zhu et al. 2023). Additionally, curcumin has been demonstrated to suppress NETosis-related enzymes in periodontitis models, which may reduce inflammation and bone resorption (Shen et al. 2024). Curcumin's medicinal benefits go beyond liver health. In sepsis, where

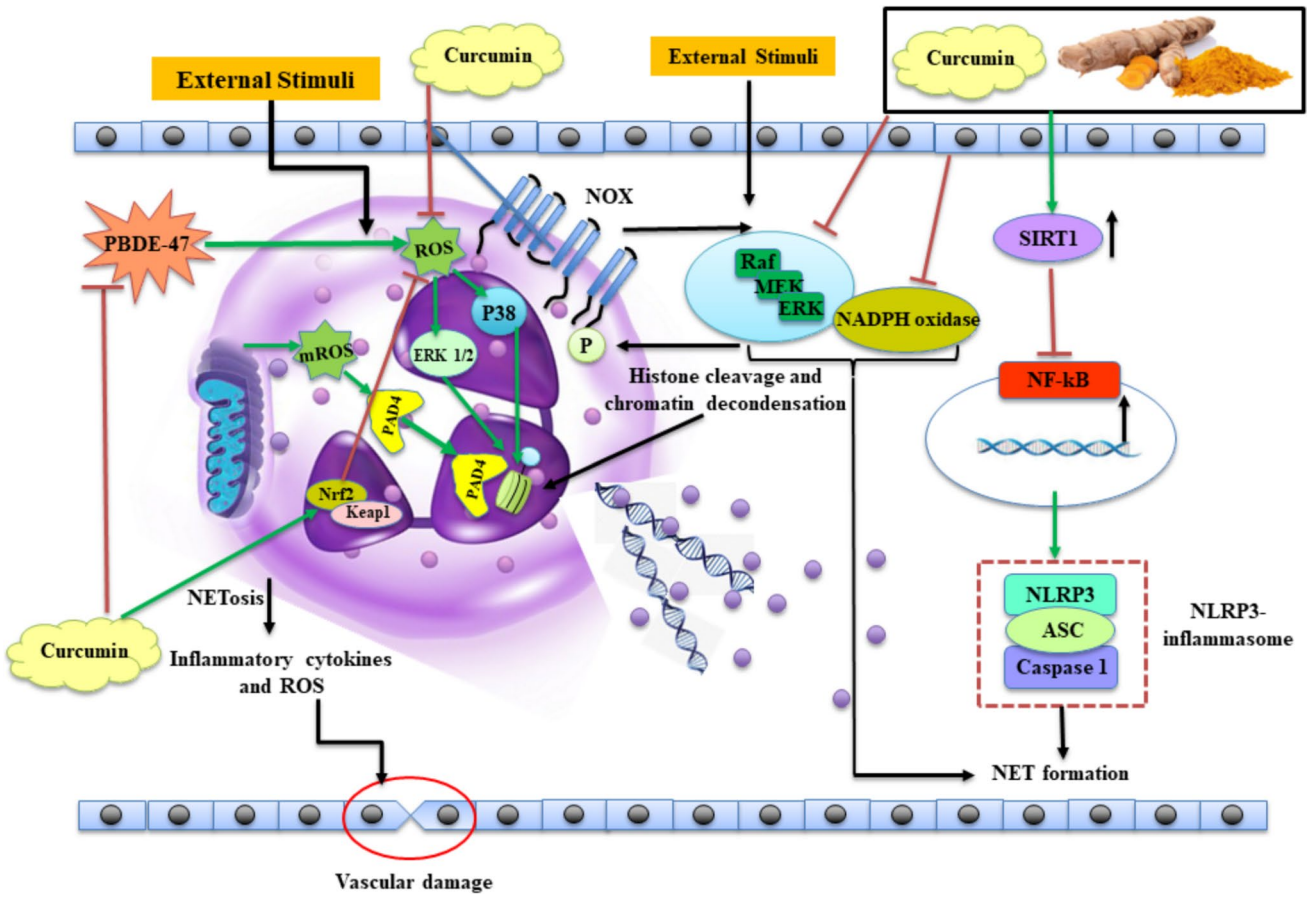


Fig. 1 The diagram depicts the processes and pathways through which curcumin inhibits NETosis. External inflammatory or infectious triggers stimulate neutrophils, initiating intracellular signaling pathways that lead to the formation of NETs. The activation of NADPH oxidase (NOX) results in the overproduction of reactive oxygen species (ROS), including mitochondrial ROS (mtROS), which act as crucial upstream signals for NETosis. ROS activate mitogen-activated protein kinase (MAPK) pathways, such as Raf–MEK–ERK1/2 and p38, which in turn promote the activation of peptidylarginine deiminase 4 (PAD4). The histone citrullination mediated by PAD4 aids in chromatin decondensation and histone cleavage, ultimately allowing for the release of NETs. Simultaneously, signaling pathways reliant on ROS and mediated by NF-κB promote the assembly and activation of the NLRP3 inflammasome complex (comprising NLRP3, ASC, and caspase-1), thereby intensifying inflammatory responses and the formation of NETs. An overabundance of NET release leads to endothelial dysfunction and vascular injury. Curcumin demonstrates inhibitory effects on NETosis across various regulatory mechanisms. It inhibits the generation of ROS derived from NOX and the phosphorylation of MAPK, restricts the activity of PAD4, and diminishes NF-κB signaling, which in turn lowers the activation of the NLRP3 inflammasome. Furthermore, curcumin boosts antioxidant defenses by activating the Nrf2–Keap1 pathway and increasing the expression of SIRT1, which together mitigate oxidative stress, the production of inflammatory cytokines, and the formation of aberrant NETs

curcumin-derived carbonized polymer dots have been demonstrated to enhance NET release for microbial trapping along with antioxidative effects, its capacity to regulate NET formation may also be advantageous (Lin et al. 2024). Moreover, it has been indicated that the detrimental effects of polybrominated diphenyl ethers (PBDE-47) can be mitigated by curcumin which inhibit the release of NETs triggered by PBDE-47 (Fig. 1). This inhibitory mechanism consequently influences the reactive oxygen species (ROS) activity associated with Nrf2 (Ye et al. 2021; Liu et al. 2024). In addition, the suppression of NLR family pyrin domain containing 3 (NLRP3) activation or the prohibition of NET formation induced by SARS-CoV-2 may represent a novel therapeutic approach for COVID-19, specially via the utilization of natural compounds such as curcumin. The Raf-MEK-ERK signaling pathway is implicated in the formation of NETs by stimulating the activity of NADPH oxidase (Fig. 1) (Hakkim et al. 2011). It remains to be explored if Curcumin can reduces NET formation through this signaling pathway.

It is clear from the observations mentioned above that curcumin may offer promising opportunities for therapeutic strategies targeting NET-mediated pathogenesis.

Current research indicates that the inhibitory effects of curcumin and other phytochemicals on NET formation are mainly linked to ROS-dependent, suicidal NETosis

(Askarizadeh et al. 2025). In these scenarios, curcumin may inhibit critical upstream processes in NETosis, including the generation of intracellular ROS, activation of the MAPK pathway, PAD4-mediated histone citrullination, and subsequent inflammatory signaling.

In contrast, the effects of curcumin on vital or ROS-independent NETosis remain insufficiently characterized (Zambrano et al. 2025). These forms of NETosis are often associated with rapid antimicrobial responses and may rely on distinct calcium-dependent or receptor-mediated pathways that have not been systematically evaluated in the context of curcumin treatment. Therefore, while curcumin appears to effectively modulate NET formation under inflammatory and pathological conditions characterized by excessive oxidative stress, its impact on alternative NETosis pathways warrants further investigation (Chen et al. 2025b).

Experimental and clinical evidence for curcumin-mediated modulation of NETosis: a critical appraisal

The present comprehension of the regulation of NET formation mediated by curcumin is mainly based on preclinical investigations, encompassing both in vitro studies and animal models, whereas direct clinical validation is still scarce. Consequently, it is crucial to differentiate between these experimental settings to guarantee a precise interpretation of the current literature. In vitro investigations utilizing isolated human or murine neutrophils have yielded significant mechanistic understanding regarding the impact of curcumin on NETosis-associated signaling pathways, which encompass ROS generation, MAPK activation, PAD4-mediated histone citrullination, and the production of inflammatory cytokines. Nevertheless, these reductionist models fail to completely replicate the intricacies of the inflammatory microenvironment, which includes cell–cell interactions, hemodynamic factors, and metabolic influences that govern NET formation in vivo (Zhu et al. 2023; Stoiber et al. 2015).

Animal models have demonstrated that neutrophils play central roles in autoimmune and inflammatory diseases through multiple mechanisms, including NET formation, T-cell and dendritic cell regulation, and cytokine production. These models have revealed common pathological themes, such as neutrophil-mediated vascular permeability in arthritis, encephalitis, and colitis (Németh et al. 2016).

Specifically, computational analysis and experimental validation in mice demonstrated that curcumin alleviates periodontitis by directly inhibiting NET formation through binding to neutrophil elastase, peptidylarginine deiminase 4, and cathepsin G (Shen et al. 2024).

Clinical and animal model evidence directly linking curcumin administration to modulation of NET formation or NET-associated biomarkers remains scarce.

Bioavailability challenges of curcumin and implications for targeting NETosis

Despite substantial evidence endorsing the anti-inflammatory and antioxidant characteristics of curcumin, its application in clinical settings is still restricted due to low oral bioavailability (El-Saadony et al. 2025). Curcumin is characterized by low solubility in water, swift metabolism in the intestines and liver, and restricted systemic exposure after oral intake. These pharmacokinetic limitations could considerably affect its effectiveness in influencing the formation of NETs, especially in pathological scenarios where prolonged and tissue-targeted drug concentrations are essential (El-Saadony et al. 2025). Regarding NETosis specifically, natural compounds including curcumin show potential as multitarget modulators, though most evidence comes from preclinical studies (Jia et al. 2025). Consequently, the translational relevance of these findings must be interpreted with caution.

To overcome these limitations, various strategies have been suggested to improve the bioavailability and therapeutic efficacy of curcumin. Nano-formulations, which include curcumin-loaded nanoparticles, liposomes, micelles, and polymeric carriers, have demonstrated potential in enhancing solubility, stability, and targeted delivery (Yan et al. 2025; Ghalandarlaki et al. 2014; Hatamipour et al. 2019). This may, in turn, augment curcumin's capacity to modulate NET-associated signaling pathways in vivo.

Alternatively, the creation of synthetic curcumin analogs that possess enhanced pharmacokinetic and metabolic characteristics signifies another encouraging strategy. Numerous analogs maintain the anti-inflammatory and antioxidant properties of natural curcumin (Ghalandarlaki et al. 2014; Martinez-Cifuentes et al. 2015; Adeleye et al. 2025; Kaur et al. 2024), while demonstrating improved stability and bioavailability, which could be beneficial for addressing NETosis in chronic inflammatory conditions.

Collectively, these strategies underscore the significance of formulation and drug design considerations in the transition of curcumin-mediated NET modulation from preclinical models to clinical application. Future research that incorporates optimized curcumin formulations alongside disease-specific NET biomarkers will be essential for confirming the therapeutic viability of targeting NETosis in human diseases.

Balancing host defense and inflammation: risks and considerations in targeting NETosis

NETs are essential components of innate immunity, functioning to capture and neutralize invading pathogens, which in turn restricts the spread of microbes during infections (Pignataro et al. 2025; Kaplan and Radic 2012). This antimicrobial activity highlights the significance of NETosis as a crucial defense mechanism for the host. Therefore, the widespread or indiscriminate inhibition of NET formation could pose potential dangers, such as heightened vulnerability to infections and compromised immune surveillance (Kaplan and Radic 2012; Retter et al. 2025).

The pathological effects of NETosis generally stem from excessive, prolonged, or dysregulated formation of NETs, rather than from the normal physiological release of NETs (Jia et al. 2025; Tang et al. 2025). In the context of chronic inflammatory and autoimmune disorders, abnormal accumulation of NETs plays a significant role in perpetuating inflammation, causing tissue damage, and leading to immune dysregulation. These findings underscore the necessity for therapeutic approaches that specifically aim to inhibit pathological NET formation while maintaining the crucial antimicrobial roles of neutrophils (Wu and Shen 2024; Chen et al. 2025a).

The modulation of NETosis by curcumin may provide a regulatory strategy that is dependent on the specific context, rather than a total suppression (Moon 2025). By diminishing the upstream inflammatory and oxidative signaling pathways such as the overproduction of ROS, activation of MAPK, and signaling through the inflammasome curcumin may selectively restrict NET formation in scenarios characterized by chronic inflammation or oxidative stress (Yang and Yang 2025; Kar et al. 2026). This regulatory influence could mitigate tissue damage and the amplification of inflammation while still allowing for rapid NET responses driven by infections.

Consequently, forthcoming interventions aimed at NET should focus on the temporal, spatial, and disease-specific regulation of NETosis. The creation of targeted delivery mechanisms, refined dosing strategies, and therapeutic approaches guided by biomarkers will be essential for striking a balance between alleviating NET-related pathology and preserving effective host defense.

Conclusion

NETs serve as a vital link between innate immunity and inflammatory disease processes. Although the normal formation of NETs plays a role in host defense, an overproduction or misregulation of NETosis can lead to tissue injury, thrombosis, and persistent inflammation in various diseases. Cumulative evidence suggests that curcumin reduces pathological NET formation by modulating several key signaling pathways at multiple levels. This includes the suppression of excessive ROS production, inhibition of MAPK (MEK/ERK and p38) signaling, reduction of PAD4-mediated histone citrullination, and downregulation of NF-κB and NLRP3 inflammasome activation.

Despite these encouraging mechanistic insights, the existing evidence primarily stems from in vitro studies and specific animal models. Future investigations should emphasize the utilization of disease-relevant in vivo models to more accurately delineate the context-dependent impacts of curcumin on NETosis and to differentiate between physiological and pathological NET responses. Simultaneously, clinical trials are necessary to assess if curcumin, especially in enhanced formulations, can successfully influence NET-related biomarkers and enhance health outcomes in individuals.

In addition, novel strategies including nano-formulated curcumin, synthetic analogs exhibiting enhanced pharmacokinetic characteristics, and combination therapies aimed at complementary NET-related pathways necessitate additional research. The incorporation of NET-specific biomarkers into both preclinical and clinical study frameworks will be crucial for converting curcumin-mediated NET modulation into practical therapeutic methods. Together, these initiatives could facilitate targeted and context-sensitive regulation of NETosis in diseases characterized by inflammation and immune mediation.

Acknowledgements None.

Author contributions AS, EM, TJ, SK and PK designed, drafted and revised the manuscript. All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

Funding None.

Data availability Not applicable.

Declarations

Conflict of interest The authors declare no conflicts of interest.

Consent to participate Not applicable.

Consent for publication Not applicable.

References

Adeleye AO, Dena SM, Oguntibeju OO, Titinchi S, Opuwari CS (2025) Overcoming curcumin's limitations: synthetic derivatives in diabetes and cancer management. Appl Res 4:e70049

Almyroudis NG, Grimm MJ, Davidson BA, Röhm M, Urban CF, Segal BH (2013) NETosis and NADPH oxidase: at the intersection of host defense, inflammation, and injury. Front Immunol 4:45

Ansari WA, Srivastava K, Nasibullah M, Khan MF (2025) Reactive oxygen species (ROS): sources, generation, disease pathophysiology, and antioxidants. Discover Chem 2:191

Askarizadeh F, Karav S, Sahebkar A (2025) Phytochemicals as modulators of NETosis: a comprehensive review on their mechanisms and therapeutic potential. Phytother Res 39:3545–3577

Azzouz D, Palaniyar N (2024) How do ROS induce NETosis? oxidative DNA damage, DNA repair, and chromatin decondensation. Biomolecules 14:1307

Bardak H, Uğuz AC, Bardak Y (2017) Curcumin regulates intracellular calcium release and inhibits oxidative stress parameters, VEGF, and caspase-3/-9 levels in human retinal pigment epithelium cells. Physiol Int 104(4):301–315

Barnado A, Crofford LJ, Oates JC (2016) At the bedside: neutrophil extracellular traps (NETs) as targets for biomarkers and therapies in autoimmune diseases. J Leucoc Biol 99:265–278

Block H, Rossaint J, Zarbock A (2022) The fatal circle of NETs and NET-associated DAMPs contributing to organ dysfunction. Cells 11:1919

Brinkmann V, Reichard U, Goosmann C, Fauler B, Uhlemann Y, Weiss DS, Weinrauch Y, Zychlinsky A (2004) Neutrophil extracellular traps kill bacteria. Sci 303:1532–1535

Camandola S, Mattson MP (2007) NF-κB as a therapeutic target in neurodegenerative diseases. Expert Opin Ther Targets 11:123–132

Chen X, Gao D, Wang M, Wang L, Hu H, Wen C, Tang Y (2025a) Neutrophil extracellular traps in systemic lupus erythematosus: pathogenic mechanisms, crosstalk with oxidative stress, and antioxidant therapeutic potential. Antioxidants 15:25

Chen YS, Tian HX, Rong DC, Wang L, Chen S, Zeng J, Xu H, Mei J, Wang LY, Liou YL, Zhou HH (2025b) ROS homeostasis in cell fate, pathophysiology, and therapeutic interventions. Mol Biomed 6:89

Cheng Y, Wang L, Zhang S, Jian W, Zeng B, Liang L, Deng Z (2025) The investigation of Nfkappab inhibitors to block cell proliferation in OSCC cells lines. Curr Med Chem 32:7314–7326

Cho KB, Park CH, Kim J, Tin TD, Kwak S-H (2020) Protective role of curcumin against lipopolysaccharide-induced inflammation and apoptosis in human neutrophil. Anesth Pain Med 15:41–48

Ciesielski O, Biesiekierska M, Panthu B, Soszyński M, Pirola L, Balcerczyk A (2022) Citrullination in the pathology of inflammatoryand autoimmune disorders: recent advances and future perspectives. Cell Mol Life Sci 79(2):94. PMID: 35079870; PMCID: PMC8788905. https://doi.org/10.1007/s00018-022-04126-3

Cui J, Li H, Zhang T, Lin F, Chen M, Zhang G, Feng Z (2025) Research progress on the mechanism of curcumin anti-oxidative stress based on signaling pathway. Front Pharmacol 16:1548073

Derochette S, Franck T, Mouithys-Mickalad A, Ceusters J, Deby-Dupont G, Lejeune JP, Neven P, Serteyn D (2013) Curcumin and resveratrol act by different ways on NADPH oxidase activity and reactive oxygen species produced byequine neutrophils. Chemico-Biol Interact 206(2):186–193. https://doi.org/10.1016/j.cbi.2013.09.011

Döring Y, Soehnlein O, Weber C (2017) Neutrophil extracellular traps in atherosclerosis and atherothrombosis. Circ Res 120:736–743

El-Saadony MT, Saad AM, Mohammed DM, Alkafaas SS, Ghosh S, Negm SH, Salem HM, Fahmy MA, Mosa WF, Ibrahim EH (2025) Curcumin, an active component of turmeric: biological activities, nutritional aspects, immunological, bioavailability, and human health benefits-a comprehensive review. Front Immunol 16:1603018

Fousert E, Toes R, Desai J (2020) Neutrophil Extracellular Traps (NETs) Take the Central Stage in Driving Autoimmune Responses. Cells 9(4):915. PMID: 32276504; PMCID: PMC7226846. https://doi.org/10.3390/cells9040915

Ghalandarlaki N, Alizadeh AM, Ashkani-Esfahani S (2014) Nanotechnology-applied curcumin for different diseases therapy. BioMed Res Int 2014:394264

Guo Q, Jin Y, Chen X, Ye X, Shen X, Lin M, Zeng C, Zhou T, Zhang J (2024) NF-κB in biology and targeted therapy: new insights and translational implications. Signal Transduct Target Ther 9:53

Hakkim A, Fuchs TA, Martinez NE, Hess S, Prinz H, Zychlinsky A, Waldmann H (2011) Activation of the Raf-MEK-ERK pathway is required for neutrophil extracellular trap formation. Nat Chem Biol 7(2):75–77. https://doi.org/10.1038/nchembio.496

Hamzehzadeh L, Atkin SL, Majeed M, Butler AE, Sahebkar A (2018) The versatile role of curcumin in cancer prevention and treatment: a focus on PI3K/AKT pathway. J Cell Physiol 233:6530–6537

Hasanzadeh S, Read MI, Bland AR, Majeed M, Jamialahmadi T, Sahebkar A (2020) Curcumin: an inflammasome silencer. Pharmacol Res 159:104921

Hatamipour M, Sahebkar A, Alavizadeh SH, Dorri M, Jaafari MR (2019) Novel nanomicelle formulation to enhance bioavailability and stability of curcuminoids. Iran J Basic Med Sci 22:282–289

Heidari H, Bagherniya M, Majeed M, Sathyapalan T, Jamialahmadi T, Sahebkar A (2023) Curcumin-piperine co-supplementation and human health: a comprehensive review of preclinical and clinical studies. Phytother Res 37:1462–1487

Islam MM, Takeyama N (2023) Role of neutrophil extracellular traps in health and disease pathophysiology: recent insights and advances. Int J Mol Sci 24:15805

Jia W, Zhang J, Shang Y, Liu S (2025) Multitarget Natural Compounds Taming NETosis: A Translational Strategy for Cancer and Inflammatory Diseases. Cancer Lett 636:218103

Kaplan MJ (2024) Exploring the role of neutrophil extracellular traps in systemic lupus erythematosus: a clinical case study and comprehensive review. Arthritis Rheumatol 77:247

Kaplan MJ, Radic M (2012) Neutrophil extracellular traps: double-edged swords of innate immunity. J Immunol 189:2689–2695

Kar SS, Mishra H, Barik CS, Kar B, Ghosh G, Rath G (2026) Targeting reactive oxygen species signaling pathways for cancer metabolic reprogramming. Elsevier, Emerg Strateg Cancer Metab

Kaur K, Al-Khazaleh AK, Bhuyan DJ, Li F, Li CG (2024) A review of recent curcumin analogues and their antioxidant, anti-inflammatory, and anticancer activities. Antioxidants 13:1092

Keshari RS, Verma A, Barthwal MK, Dikshit M (2013) Reactive oxygen species-induced activation of ERK and p38 MAPK mediates PMA-induced NETs release from human neutrophils. J Cell Biochem 114:532–540

Kijak-Boćkowska M, Czerwińska J, Owczarczyk-Saczonek A (2025) Peptidylarginine deiminases: an overview of recent advances in citrullination research. Int J Mol Sci 26:12060

Kimball AS, Obi AT, Diaz JA, Henke PK (2016) The emerging role of NETs in venous thrombosis and immunothrombosis. Front Immunol 7:236

Lee H, Jose PA (2021) Coordinated contribution of NADPH oxidase- and mitochondria-derived reactive oxygen species in metabolic syndrome and its implication in renal dysfunction. Front Pharmacol 12:670076

Li N, Yin C, Tao J (2025) Neutrophil extracellular traps in tumor metastasis: mechanisms, and therapeutic implications. Discover Oncol 16:1631

Liao F, Fan J, Wang R, Xu Z, Li Q, Bi W, Deng J, Jiang J, Wang Z, Zeng L (2025) Neutrophil extracellular traps in sepsis: trade-off between pros and cons. Burns Trauma 13:tkaf046

Liczbiński P, Michałowicz J, Bukowska B (2020) Molecular mechanism of curcumin action in signaling pathways: review of the latest research. Phytother Res 34:1992–2005

Lin CJ, Hwang TL, Wang RY, Nain A, Shih RH, Chang L, Lin HJ, Harroun SG, Chang HT, Huang CC (2024) Augmenting Neutrophil Extracellular Traps with carbonized polymer dots: a potential treatment for bacterial sepsis. Small. https://doi.org/10.1002/smll.202307210

Liu Y, Kaplan MJ (2021) Neutrophils in the pathogenesis of rheumatic diseases: fueling the fire. Clin Rev Allergy Immunol 60:1–16

Liu T, Zhang L, Joo D, Sun S-C (2017) NF-κB signaling in inflammation. Signal Transduct Target Ther 2:1–9

Liu X, Arfman T, Wichapong K, Reutelingsperger CP, Voorberg J, Nicolaes GA (2021) PAD4 takes charge during neutrophil activation: impact of PAD4 mediated NET formation on immune-mediated disease. J Thromb Haemost 19:1607–1617

Liu ML, Lyu X, Werth VP (2022) Recent progress in the mechanistic understanding of NET formation in neutrophils. FEBS J 289:3954–3966

Liu R, Zhang J, Lima FR, Zeng J, Nian Q (2024) Targeting neutrophil extracellular traps: a novel strategy in hematologic malignancies. Biomed Pharmacother 173:116334

Ma Y, Zhang J, Qi Y, Lu Y, Dong Y, Hu D (2025) Neutrophil Extracellular Traps in Cardiovascular Diseases: Pathological Roles and Therapeutic Implications. Biomolecules 15(9):1263. https://doi.org/10.3390/biom15091263

Maronek M, Gardlik R (2022) The citrullination-neutrophil extracellular trap axis in chronic diseases. J Innate Immun 14:393–417

Martinez-Cifuentes M, Weiss-Lopez B, Santos SL, Araya-Maturana R (2015) Heterocyclic curcumin derivatives of pharmacological interest: recent progress. Curr Top Med Chem 15:1663–1672

Mirhadi E, Tasbandi A, Kesharwani P, Sahebkar A (2024) Curcumin: historical background, introduction, structure, and physicochemical attributes. Elsevier, Curcumin-Based Nanomedicines as Cancer Therapeutics

Momtazi-Borojeni AA, Sahebkar A (2016) Difluorinated curcumin: a promising curcumin analogue with improved anti-tumor activity and pharmacokinetic profile. Curr Pharm des 22:4386–4397

Moon DO (2025) Curcumin as a dual modulator of pyroptosis: mechanistic insights and therapeutic potential. Int J Mol Sci 26:7590

Morawiec M-L, Kubina R, Jabłońska E, Ratajczak-Wrona W, Stępień S, Gołębski M, Mielczarek-Palacz A (2025) NETs-as predictors and targets of supportive therapy for cancer treatment. Front Immunol 16:1666261

Morshed M, Hlushchuk R, Simon D, Walls AF, Obata-Ninomiya K, Karasuyama H, Djonov V, Eggel A, Kaufmann T, Simon H-U (2014) NADPH oxidase–independent formation of extracellular DNA traps by basophils. J Immunol 192:5314–5323

Mutua V, Gershwin LJ (2021) A review of neutrophil extracellular traps (NETs) in disease: potential anti-NETs therapeutics. Clin Rev Allergy Immunol 61:194–211

Németh T, Mócsai A, Lowell CA (2016) Neutrophils in animal models of autoimmune disease. Semin Immunol 174–186

Ng GYQ, Loh ZW-L, Fann DY, Mallilankaraman K, Arumugam TV, Hande MP (2024) Role of mitogen-activated protein (MAP) kinase pathways in metabolic diseases. Genome Integr 15:e20230003

Panahi Y, Ghanei M, Bashiri S, Hajihashemi A, Sahebkar A (2014) Short-term curcuminoid supplementation for chronic pulmonary complications due to sulfur mustard Intoxication: positive results of a randomized double-blind placebo-controlled trial. Drug Res 65:567–573

Pignataro G, Gemma S, Petrucci M, Barone F, Piccioni A, Franceschi F, Candelli M (2025) Unraveling NETs in sepsis: from cellular mechanisms to clinical relevance. Int J Mol Sci 26:7464

Retter A, Singer M, Annane D (2025) The NET effect: neutrophil extracellular traps—a potential key component of the dysregulated host immune response in sepsis. Crit Care 29:59

Saberi-Karimian M, Keshvari M, Ghayour-Mobarhan M, Salehizadeh L, Rahmani S, Behnam B, Jamialahmadi T, Asgary S, Sahebkar A (2020) Effects of curcuminoids on inflammatory status in patients with non-alcoholic fatty liver disease: a randomized controlled trial. Complement Ther Med. https://doi.org/10.1016/j.ctim.2020.102322

Sadeghi M, Dehnavi S, Asadirad A, Xu S, Majeed M, Jamialahmadi T, Johnston TP, Sahebkar A (2023) Curcumin and chemokines: mechanism of action and therapeutic potential in inflammatory diseases. Inflammopharmacology 31:1069–1093

Sendtner N, Seitz R, Brandl N, Müller M, Gülow K (2025) Reactive oxygen species across death pathways: Gatekeepers of apoptosis, ferroptosis, pyroptosis, paraptosis, and beyond. Int J Mol Sci 26:10240

Shafabakhsh R, Pourhanifeh MH, Mirzaei HR, Sahebkar A, Asemi Z, Mirzaei H (2019) Targeting regulatory T cells by curcumin: a potential for cancer immunotherapy. Pharmacol Res. https://doi.org/10.1016/j.phrs.2019.104353

Shahzad A, Ni Y, Yang Y, Liu W, Teng Z, Bai H, Liu X, Sun Y, Xia J, Cui K (2025) Neutrophil extracellular traps (NETs) in health and disease. Mol Biomed 6:130

Shamsnia HS, Roustaei M, Ahmadvand D, Butler AE, Amirlou D, Soltani S, Momtaz S, Jamialahmadi T, Abdolghaffari AH, Sahebkar A (2023) Impact of curcumin on p38 MAPK: therapeutic implications. Inflammopharmacology 31(5):2201–2212. https://doi.org/10.1007/s10787-023-01265-2

Shen D, Tuerhong K, Huang Q, Liu K, Li Y, Yang S (2024) Computational analysis of curcumin-mediated alleviation of inflammation in periodontitis patients with experimental validation in mice. J Clin Periodontol 51:787–799

Shen Y, Fang H, Xie H, Zhu S, Wang X, Liu S, Sui J, Xu Y, Bo Y, Zhao J (2025) Neutrophils and neutrophil extracellular traps: double-edged swords in cancer pathophysiology and therapy resistance. Cell Commun Signal 23:476

Song P, Zou M-H (2015) Roles of Reactive Oxygen Species in Physiology and Pathology. Atherosclerosis

Stoiber W, Obermayer A, Steinbacher P, Krautgartner W-D (2015) The role of reactive oxygen species (ROS) in the formation of extracellular traps (ETs) in humans. Biomolecules 5:702–723

Szymańska Z, Staniewski A, Karpiński M, Zalewska K, Kalus O, Gramala Z, Maćkowiak J, Mertowski S, Filipiak KJ, Rahnama-Hezavah M (2025) The role of neutrophil extracellular networks in cardiovascular pathology. Cells 14:1562

Tang R, Yin J, Qin Z, Zhang M, Jia X (2025) NETs: a new target for autoimmune disease. Front Immunol 16:1646527

Tao H, Yuan Y, Chen C, Hong J, Wen Y, Zhang H (2026) Curcumin alleviates dry/heat stress-induced acute kidney injury by reducing the formation of neutrophil extracellular traps in rats. Eur J Pharmacol 1019:178696. PMID: 41759883. https://doi.org/10.1016/j.ejphar.2026.178696

Thakur M, Evans B, Schindewolf M, Baumgartner I, Doering Y (2021) Neutrophil extracellular traps affecting cardiovascular health in infectious and inflammatory diseases. Cells 10:1689

Thiam HR, Wong SL, Wagner DD, Waterman CM (2020) Cellular mechanisms of netosis. Annu Rev Cell Dev Biol 36:191–218

Vorobjeva N, Chernyak B (2020) NETosis: molecular mechanisms, role in physiology and pathology. Biochem Mosc 85:1178–1190

Wang W, Li M, Wang L, Chen L, Goh BC (2023) Curcumin in cancer therapy: exploring molecular mechanisms and overcoming clinical challenges. Cancer Lett 570:216332

Wei S, Ma W, Li X, Jiang C, Sun T, Li Y, Zhang B, Li W (2020) Involvement of ROS/NLRP3 inflammasome signaling pathway in Doxorubicin-induced cardiotoxicity. Cardiovasc Toxicol 20:507–519

Wigerblad G, Kaplan MJ (2023) Neutrophil extracellular traps in systemic autoimmune and autoinflammatory diseases. Nat Rev Immunol 23:274–288

Wójcik P, Gęgotek A, Žarković N, Skrzydlewska E (2021) Oxidative stress and lipid mediators modulate immune cell functions in autoimmune diseases. Int J Mol Sci 22:723

Wu Y, Shen J (2024) Unraveling the intricacies of neutrophil extracellular traps in inflammatory bowel disease: pathways, biomarkers, and promising therapies. Cytokine Growth Factor Rev 80:156–167

Wu C, Xu X, Shi Y, Li F, Zhang X, Huang Y, Xia D (2024) Neutrophil extracellular trap formation model induced by monosodium urate and phorbol myristate acetate: involvement in MAPK signaling pathways. Int J Mol Sci 26:143

Xiong J, Xue J, Zhou H, Qi W, Zhu H (2025) The crosstalk of neutrophil extracellular trap-inflammasome and their roles in disease progression. Mol Aspects Med 106:101419

Xu Y, Zhang J, Han J, Pan X, Cao Y, Guo H, Pan Y, An Y, Li X (2012) Curcumin inhibits tumor proliferation induced by neutrophil elastase through the upregulation of α1-antitrypsin in lung cancer. Mol Oncol 6:405–417

Xu A, Deng F, Chen Y, Kong Y, Pan L, Liao Q, Rao Z, Xie L, Yao C, Li S, Zeng X, Zhu X, Liu H, Gao N, Xue L, Chen F, Xu G, Wei D, Zhou X, Li Z, Sheng X (2020) NF-kappaB pathway activation during endothelial-to-mesenchymal transition in a rat model of Doxorubicin-induced cardiotoxicity. Biomed Pharmacother 130:110525

Xuan N, Zhao J, Kang Z, Cui W, Tian B-P (2024) Neutrophil extracellular traps and their implications in airway inflammatory diseases. Front Med 10:1331000

Yadav R, Momin A, Godugu C (2023) DNase based therapeutic approaches for the treatment of NETosis related inflammatory diseases. Int Immunopharmacol 124:110846

Yan Z, Chen Q, Xia Y (2023) Oxidative stress contributes to inflammatory and cellular damage in Systemic Lupus Erythematosus: cellular markers and molecular mechanism. J Inflamm Res. https://doi.org/10.2147/jir.s399284

Yan Y, Sun Y, Li Y, Wang Z, Xue L, Wang F (2025) Advancing cancer therapy: nanomaterial-based encapsulation strategies for enhanced delivery and efficacy of curcumin. Mater Today Bio. https://doi.org/10.1016/j.mtbio.2025.101963

Yang S, Yang X (2025) The role of reactive oxygen species (ROS) in periodontitis: a potential therapeutic target. Immun Inflamm Dis 13:e70301

Ye S, Li S, Ma Y, Hu D, Xiao F (2021) Curcumin hinders PBDE-47-induced neutrophil extracellular traps release via Nrf2-associated ROS inhibition. Ecotoxicol Environ Saf 225:112779

Yu HS, Cho H, Shin YU, Hong EH, Koh S-H (2025) Protective effect of curcumin in oxidative stress-induced injury on retinal pigment epithelial cells. J Clin Med 14:7153

Zambrano F, Uribe P, Schulz M, Hermosilla C, Taubert A, Sánchez R (2025) Antioxidants as modulators of NETosis: mechanisms, evidence, and therapeutic potential. Int J Mol Sci 26:5272

Zeng L, Xiang W, Xiao W, Wu Y, Sun L (2025) The emerging role of neutrophil extracellular traps in autoimmune and autoinflammatory diseases. MedComm 6:e70101

Zhu C, Shi S, Jiang P, Huang X, Zhao J, Jin Y, Shen Y, Zhou X, Liu H, Cai J (2023) Curcumin alleviates hepatic ischemia-reperfusion injury by inhibiting neutrophil extracellular traps formation. J Invest Surg 36:2164813

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.