

AYURVEDIC MEDICINAL PLANTS IN THE REGULATION OF INFLAMMATION AND OXIDATIVE STRESS: MOLECULAR MECHANISMS AND THERAPEUTIC PERSPECTIVES

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ABSTRACT

Inflammation and oxidative stress are closely related processes involved in the pathogenesis and progression of several chronic disorders such as metabolic, cardiovascular, neurodegenerative and inflammatory diseases. Excessive production of reactive oxygen species (ROS) can activate redox-sensitive inflammatory pathways and sustained inflammation can further promote oxidative damage creating a self-reinforcing cycle of cellular injury. Ayurvedic medicinal plants are rich source of bioactive phytochemicals with potential antioxidant and anti-inflammatory properties. Selected plants, including *Curcuma longa*, *Withania somnifera*, *Azadirachta indica*, *Boswellia serrata*, *Ocimum* spp., *Phyllanthus emblica*, and *Zingiber officinale*, contain diverse phytochemicals that may influence inflammatory signaling and cellular redox regulation. These effects have been related to the modulation of nuclear factor- κ B (NF- κ B), nuclear factor erythroid 2-related factor 2 (Nrf2), mitogen-activated protein kinases (MAPKs), NLRP3 inflammasome, cyclooxygenase-2 (COX-2), inducible nitric oxide synthase (iNOS) and pro-inflammatory cytokines. However, most of the available evidence is still pre-clinical, and clinical translation is still hampered by variability in phytochemical composition, extraction methods, dosage, bioavailability and standardisation. This mini-review summarises the molecular crosstalk between inflammation and oxidative stress and critically appraises selected Ayurvedic medicinal plants, their major bioactive constituents, molecular targets, and therapeutic potential with emphasis on current evidence, limitations and future research directions.

Keywords: Ayurveda; medicinal plants; inflammation; oxidative stress; phytochemicals

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1. Introduction

Inflammation is an essential response to infections, tissue damage and harmful stimuli. Acute inflammation is important for host defense and tissue repair but its persistent or dysregulated activation can contribute to chronic disorders such as metabolic, cardiovascular, neurodegenerative, autoimmune and malignant diseases (Upadhyay et al. 2025). This process is highly associated with oxidative stress. An excess of reactive oxygen species (ROS) may disturb cellular redox homeostasis and initiate inflammatory signaling and vice versa, persistent inflammation can promote ROS production, creating a self-propagating cycle of cellular damage (Prasad et al. 2021). The cross-talk between oxidative stress and inflammation is mainly governed by interconnected pathways. Nuclear factor- κ B (NF- κ B) is a key inflammatory transcription factor. The Keap1-Nrf2-antioxidant response element (ARE) system is critical for maintenance of the cellular antioxidant defence. Nrf2 activation promotes the expression of cytoprotective genes, including heme oxygenase-1 (HO-1) and NAD(P)H quinone oxidoreductase 1 (NQO1), and is functionally linked with inflammatory signaling (Saha et al. 2020). Other pathways, including mitogen-activated

protein kinases (MAPKs) and the NLRP3 inflammasome, further connect oxidative stress with inflammatory responses.

Ayurvedic medicinal plants are an important source of phytochemicals with reported antioxidant and anti-inflammatory activities. Recent molecular studies have highlighted the potential of plants such as *Curcuma longa*, *Withania somnifera*, *Boswellia serrata*, *Azadirachta indica*, *Ocimum* spp., *Phyllanthus emblica*, and *Zingiber officinale* to modulate inflammatory mediators and redox-sensitive pathways (Upadhyay et al. 2025). Computational approaches, including network pharmacology and molecular docking, are also increasingly being used to explore the multi-target actions of Ayurvedic phytoconstituents (Tambe et al. 2025). Despite growing evidence, most findings remain preclinical, and differences in phytochemical composition, extraction, dosage, bioavailability, and standardization limit clinical translation. Therefore, this mini-review summarizes the molecular relationship between inflammation and oxidative stress and critically examines selected Ayurvedic medicinal plants, their bioactive constituents, molecular targets, and therapeutic potential.

2. Inflammation and Oxidative Stress: Molecular Link

Chronic disease involves a tight interplay between inflammation and oxidative stress that enhances each other. Mitochondrial metabolism and immune-cell activation lead to the production of reactive oxygen species (ROS) which at physiological concentrations act as signalling molecules in cells, whereas high ROS concentrations trigger redox imbalance and activate inflammatory pathways, particularly nuclear factor- κ B (NF- κ B) and mitogen-activated protein kinases (MAPKs) (Albano et al. 2022). NF- κ B regulates the expression of several inflammatory mediators, including tumor necrosis factor- α (TNF- α), interleukin-6 (IL-6), cyclooxygenase-2 (COX-2), and inducible nitric oxide synthase (iNOS). ROS can promote NF- κ B signaling, while inflammatory responses can further increase ROS generation, establishing a positive feedback loop (Morgan and Liu 2011). MAPK signaling through ERK, JNK and p38 also connects cellular stress to inflammatory gene expression and cell survival responses (McCubrey, LaHair, and Franklin 2006).

In contrast, the Keap1-Nrf2-ARE pathway is one of the important endogenous antioxidant defence system. Oxidative or electrophilic stress results

in Nrf2 stabilisation and activation of antioxidant genes like heme oxygenase-1 (HO-1) and NAD(P)H quinone oxidoreductase 1 (NQO1) (Saha et al., 2020). The NLRP3 inflammasome adds another connection of oxidative stress with inflammation by triggering maturation of IL-1 β and IL-18 upon cell stress and danger signals (Zhang et al. 2023). In general, ROS, NF- κ B, MAPK, Nrf2 and NLRP3 constitute an interconnected molecular network in which oxidative stress might exacerbate inflammatory response and chronic inflammation might aggravate redox imbalance. This interaction offers a mechanistic basis for exploring Ayurvedic phytochemicals as potential multi-target modulators of inflammation and oxidative stress.

3. Ayurvedic Medicinal Plants and Their Bioactive Compounds

Ayurvedic medicinal plants contain diverse phytochemicals, including polyphenols, flavonoids, terpenoids, alkaloids, and steroidal lactones. Many of these compounds can influence multiple inflammatory and redox-sensitive pathways, supporting their potential as multi-target modulators of inflammation and oxidative stress (Upadhyay et al. 2025). The major bioactive constituents and associated molecular targets of the

selected Ayurvedic medicinal plants are summarized in Table 1.

3.1 *Curcuma longa* L. (Turmeric)

Curcuma longa is rich in curcuminoids, particularly curcumin, which has been reported to modulate NF- κ B, MAPK, COX-2, cytokine signaling, and Nrf2-mediated antioxidant responses (Prasad et al. 2021). Clinical evidence is comparatively stronger for curcumin than for many other Ayurvedic phytochemicals; a recent meta-analysis reported improvements in several inflammatory and oxidative-stress biomarkers following curcumin supplementation (Kavyani et al. 2024). Limited bioavailability, however, remains an important translational challenge.

3.2 *Withania somnifera* (L.) Dunal (Ashwagandha)

The major bioactive constituents of *W. somnifera* are steroidal lactones known as withanolides, particularly withaferin A. These compounds have been investigated for their effects on NF- κ B, JAK/STAT, MAPK, and antioxidant signaling, with evidence supporting potential anti-inflammatory and cytoprotective activities (Upadhyay et al. 2025). However, most mechanistic evidence remains preclinical.

3.3 *Boswellia serrata* Roxb. (Salai Guggul)

The resin of *B. serrata* contains boswellic acids, including acetyl-11-keto- β -boswellic acid (AKBA), which are primarily associated with inhibition of 5-lipoxygenase and leukotriene biosynthesis. Additional effects on NF- κ B, MAPK, and other inflammatory pathways have also been reported. Poor solubility and variable bioavailability of boswellic acids remain important limitations to their therapeutic translation.

3.4 *Azadirachta indica* A. Juss. (Neem)

Azadirachta indica contains limonoids and other bioactive compounds, including nimbin, nimbidin, and azadirachtin. Experimental studies suggest that Neem constituents can influence inflammatory mediators and oxidative-stress responses (Upadhyay et al. 2025). However, evidence for individual constituents remains less standardized than that available for extensively studied compounds such as curcumin.

3.5 *Ocimum tenuiflorum* L. (Tulsi)

Ocimum tenuiflorum contains phenolic and volatile constituents, including eugenol, rosmarinic acid, and ursolic acid. These compounds have demonstrated potential antioxidant and anti-inflammatory effects through modulation of inflammatory mediators

and redox-sensitive signaling. Variation in species, plant parts, extraction procedures, and phytochemical composition remains a major challenge when comparing studies.

3.6 *Phyllanthus emblica* L. (Amla)

Phyllanthus emblica is rich in polyphenols, including gallic acid, ellagic acid, and hydrolysable tannins. The antioxidant activity reported for it is associated with both direct ROS-scavenging capacity and modulation of endogenous antioxidant defences. Preliminary evidence also indicates anti-

inflammatory effects although the role of individual constituents needs further clarification.

3.7 *Zingiber officinale* Roscoe (Ginger)

Ginger is rich in phenolic compounds such as gingerols and shogaols, which have been studied for their antioxidant and anti-inflammatory activities. These constituents can modulate cyclooxygenase and lipoxygenase pathways and other inflammatory mediators, endorsing the potential of *Z. officinale* as a multi-target medicinal plant.

Table 1. Selected Ayurvedic medicinal plants, major constituents, and molecular relevance

Medicinal plant	Major bioactive constituents	Key molecular targets/pathways	Major reported activity
<i>Curcuma longa</i>	Curcumin, demethoxycurcumin	NF-κB, Nrf2, MAPK, COX-2	Anti-inflammatory, antioxidant
<i>Withania somnifera</i>	Withaferin A, withanolides	NF-κB, JAK/STAT, MAPK	Anti-inflammatory, cytoprotective
<i>Boswellia serrata</i>	AKBA, boswellic acids	5-LOX, NF-κB, MAPK	Anti-inflammatory
<i>Azadirachta indica</i>	Nimbin, nimbidin, azadirachtin	NF-κB, inflammatory mediators	Anti-inflammatory, antioxidant
<i>Ocimum tenuiflorum</i>	Eugenol, rosmarinic acid, ursolic acid	NF-κB, MAPK, redox pathways	Anti-inflammatory, antioxidant
<i>Phyllanthus emblica</i>	Gallic acid, ellagic acid, tannins	Nrf2, redox and inflammatory pathways	Antioxidant, anti-inflammatory
<i>Zingiber officinale</i>	Gingerols, shogaols	COX, LOX, inflammatory signaling	Anti-inflammatory, antioxidant

Collectively, these plants contain a redox-regulatory networks. Biological variety of chemical constituents that may outcomes can be greatly influenced by converge on common inflammatory and phytochemical composition, method of

extraction, dose, bioavailability, and experimental conditions. Thus, the molecular activity as reported should not be directly translated to clinical efficacy. [Table 1]

4. Molecular Mechanisms of Action

The biological effects of Ayurvedic medicinal plants are associated with the modulation of intertwined inflammatory and antioxidant pathways, and not with a single molecular target. Their phytochemicals can modulate transcription factors, inflammatory enzymes, cytokines and cellular antioxidant defences.

4.1 NF- κ B and MAPK Signaling

NF- κ B is a major regulator of inflammatory gene expression and controls the expression of mediators like TNF- α , IL-6, COX-2 and iNOS. Phytochemicals such as curcumin, withanolides and boswellic acids are known to modulate NF- κ B activation (Prasad et al. 2021; Upadhyay et al. 2025). MAPK pathways, particularly p38, JNK, and ERK, also respond to oxidative and inflammatory stimuli and contribute to inflammatory mediator production.

4.2 Nrf2/HO-1 Pathway

The Keap1-Nrf2 pathway is a major cellular defense mechanism against oxidative stress. Under oxidative conditions, Nrf2 activation promotes

expression of antioxidant and cytoprotective genes, including HO-1 and NQO1 ((Saha et al. 2020). Several plant-derived phytochemicals can enhance Nrf2-associated responses, thereby supporting endogenous antioxidant capacity and limiting ROS-mediated damage.

4.3 NLRP3 Inflammasome

NLRP3 provides an important link between cellular stress and inflammation. Its activation promotes caspase-1-dependent maturation of IL-1 β and IL-18 and may trigger pyroptosis (Zhang et al. 2023). Oxidative stress and mitochondrial dysfunction can contribute to NLRP3 activation, making this pathway a potential target of antioxidant and anti-inflammatory phytochemicals.

4.4 COX-2, iNOS and Cytokines

COX-2 and iNOS are important mediators of sustained inflammatory responses. Ayurvedic phytochemicals have been reported to modulate their expression together with pro-inflammatory cytokines such as TNF- α , IL-1 β , and IL-6 (Prasad et al. 2021). Collectively, regulation of NF- κ B/MAPK, Nrf2/HO-1, NLRP3, COX-2, and iNOS provides a plausible molecular basis for the multi-target activity of Ayurvedic medicinal plants against oxidative stress-associated inflammation.

5. Therapeutic Evidence, Challenges and Future Perspectives

Experimental studies support the potential of several Ayurvedic medicinal plants and their phytochemicals to modulate inflammatory and oxidative-stress responses (Prasad et al. 2021; Upadhyay et al. 2025). Among these, curcumin has comparatively stronger clinical evidence, with recent meta-analyses reporting improvements in selected inflammatory and oxidative-stress biomarkers following supplementation (Kavyani et al. 2024). Evidence for *Boswellia serrata*, *Withania somnifera*, *Zingiber officinale*, and other plants is promising but remains less consistent and is often based on preclinical or small clinical studies. Several factors currently limit the clinical translation. Variations in species, cultivation, extraction methods, phytochemical composition, dosage and formulation can affect biological activity and reproducibility. Another major challenge is the low bioavailability of compounds such as curcumin and boswellic acids. Also, safety, herb-drug interactions and long-term effects need to be systematically evaluated.

Future research must emphasise on standardised preparations, pharmacokinetic and bioavailability studies, validated molecular targets and

well-designed clinical trials. Modern approaches such as network pharmacology and multi-omics can complement experimental studies and aid in elucidating multi-target mechanisms and identifying promising phytochemicals for further validation. Ayurvedic medicinal plants will be relevant to therapeutics only if they are combined with reproducible molecular and clinical evidence with traditional knowledge.

CONCLUSION:

Ayurvedic medicinal plants represent a valuable source of bioactive compounds with potential to modulate the interconnected processes of inflammation and oxidative stress. Evidence from experimental and emerging clinical studies indicates that phytochemicals such as curcumin, withanolides, and boswellic acids can influence key pathways including NF- κ B, MAPK, Nrf2/HO-1, NLRP3, COX-2, and iNOS. However, the therapeutic significance of these effects should be interpreted cautiously because much of the available evidence remains preclinical and substantial variation exists in phytochemical composition, dosage, bioavailability, and formulation. Future research should emphasize standardized preparations, molecular validation, pharmacokinetic characterization, and

well-designed clinical trials. Integrating traditional Ayurvedic knowledge with modern molecular and computational approaches may help identify reproducible, mechanism-based applications of medicinal plants for inflammation- and oxidative stress-related disorders.

DECLARATIONS

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA

No new datasets were generated or analyzed in this study. Information discussed in this mini-review was obtained from

publicly available scientific literature and cited appropriately in the manuscript.

COMPETING INTERESTS

Not applicable.

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AUTHOR CONTRIBUTIONS

Prashant Kumar Tiwari and Sanjay Kumar conceptualized the review, defined its scope, and contributed to the literature analysis and preparation of the manuscript.

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