RESEARCH PAPER

Phytotherapeutic Strategies for Bronchial Asthma: A Comprehensive Review of Anti-Inflammatory Medicinal Plants, Bioactive Compounds, and Molecular Mechanisms

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Received: 16th Dec, 2025; Revised: 8th Feb 2026; Accepted: 24th Feb, 2026; Available Online: 30th March, 2026

ABSTRACT

Background: Bronchial asthma and chronic inflammatory disorders represent a significant global health burden, particularly in low- and middle-income countries where access to pharmacotherapy remains limited. Conventional treatments, although effective, are associated with adverse effects, drug resistance, and high costs, necessitating alternative therapeutic approaches.

Objective: This review aims to comprehensively evaluate medicinal plants with anti-asthmatic and anti-inflammatory potential, focusing on bioactive compounds, pharmacological mechanisms, and clinical relevance.

Methods: Relevant literature was systematically collected from databases including PubMed, Scopus, and Web of Science. Studies involving phytochemical analysis, in vitro/in vivo models, and clinical trials were included.

Results: Numerous medicinal plants such as Nigella sativa, Ocimum sanctum, Curcuma longa, and Glycyrrhiza glabra demonstrated significant anti-inflammatory and bronchodilatory activities. Key bioactive compounds including flavonoids, alkaloids, terpenoids, and phenolics were found to modulate inflammatory pathways such as NF-κB, cytokine signaling, and oxidative stress.

Conclusion: Phytotherapy offers promising alternatives for asthma management. However, further clinical validation and standardization are essential to ensure safety and efficacy.

Keywords: Bronchial asthma, Medicinal plants, Anti-inflammatory, Phytotherapy, Bioactive compounds, Herbal medicine

How to cite this article: Mirza K.A., Kawhale S. N., Ghube D. D., Tathe P. R., Phytotherapeutic Strategies for Bronchial Asthma: A Comprehensive Review of Anti-Inflammatory Medicinal Plants, Bioactive Compounds, and Molecular Mechanisms. Int J Drug Deliv Technol. 2026;16(21s): 230-245. DOI: 10.25258/ijddt.16.21s.24

Source of support: Nil.

Conflict of interest: None

1. INTRODUCTION

Respiratory diseases represent one of the foremost contributors to global morbidity and mortality, with bronchial asthma alone accounting for more than 455,000 deaths annually and affecting an estimated 339 million individuals across diverse demographic and geographic settings [1]. The disproportionate burden borne by low- and middle-income nations — where upward of 80% of asthma-related fatalities occur — reflects not only biological susceptibility to environmental triggers but also structural inequities in healthcare access, drug affordability, and diagnostic infrastructure [1,2]. Despite substantial pharmacological advances over the past four decades, asthma management remains suboptimal in a significant proportion of patients, particularly those with severe or treatment-refractory phenotypes.

Inflammation constitutes the shared mechanistic substrate underlying bronchial asthma, and a remarkably broad spectrum of systemic non-communicable conditions such inflammatory bowel disease, cardiovascular disease, and rheumatoid arthritis pathology, metabolic syndrome, psoriasis, and certain malignancies [3]. The dysregulation of innate and adaptive immune responses —

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manifesting as aberrant cytokine production, leukocyte trafficking, eicosanoid biosynthesis, and reactive oxygen species (ROS) generation — drives both acute inflammatory episodes and the pathological tissue remodeling characteristic of chronic inflammatory conditions [4]. Pharmacological modulation of these shared molecular targets therefore presents opportunities for broadly applicable anti-inflammatory therapeutics.

The contemporary pharmacopoeia for asthma and inflammatory diseases encompasses inhaled corticosteroids (ICS), beta-2 adrenoceptor agonists (short- and long-acting), leukotriene receptor antagonists, phosphodiesterase-4 inhibitors, methylxanthines, biologic agents targeting IgE and specific cytokine pathways, and conventional NSAIDs and DMARDs for systemic inflammatory conditions [5]. While these agents have transformed the clinical management of these diseases, their deployment in real-world practice is constrained by multiple factors: corticosteroid-associated adverse effects (hypothalamic-pituitary-adrenal axis suppression, osteoporosis, metabolic disturbances, susceptibility to opportunistic infections), high costs of biologic therapies precluding universal access, NSAID-associated gastrointestinal and renal toxicity, and the absence of disease- modifying treatments that can reliably halt or reverse airway remodeling [5,6].

These pharmacological limitations, combined with a global renaissance of interest in traditional and complementary medicine systems, have positioned phytotherapy as a scientifically legitimate and clinically relevant field of inquiry. Medicinal plants constitute structurally diverse, evolutionarily optimized repositories of bioactive molecules — many representing the evolutionary scaffolds from which modern drugs have been derived or inspired. Aspirin originated from salicylate-rich willow bark; ephedrine, the prototypal bronchodilator, was isolated from Ephedra sinica; and Artemisia annua is the source of the antimalarial artemisinin [7]. According to estimates from the World Health

Organization, almost 80% of people worldwide use plant-based medications for primary healthcare, underscoring the practical and cultural significance of this therapeutic tradition [8].

Modern pharmacognosy and molecular pharmacology have progressively elucidated the mechanistic bases of empirically observed herbal therapeutic effects, identifying specific phytoconstituents and characterizing their molecular targets within inflammatory and bronchospastic cascades. Compounds such as curcumin (from Curcuma longa), thymoquinone (from Nigella sativa), 1,8- cineole (from Eucalyptus globulus), and apocynin (from Picrorhiza kurroa) have been demonstrated to interact with multiple validated pharmacological targets including NF-κB, COX-2, 5-LOX, TNF- α, and specific interleukin receptors [9,10]. This multi-target pharmacological profile — frequently cited as a theoretical advantage over single-target synthetic drugs in the context of complex multifactorial diseases — warrants rigorous systematic evaluation.

This comprehensive review aims to: (i) provide a detailed pathophysiological framework for understanding asthma and inflammatory disease mechanisms; (ii) critically evaluate the phytochemical constituents and pharmacological activities of fifteen pharmacologically significant medicinal plants; (iii) synthesize available preclinical and clinical evidence supporting their anti- asthmatic and anti-inflammatory applications; (iv) compare herbal mechanisms with those of conventional drugs; and (v) identify critical research gaps and propose directions for future scientific investigation. By incorporating conventional ethnopharmacological familiarity with current molecular pharmacological evidence, this review aims to contribute substantively to the growing body of literature supporting evidence-based phytotherapy in respiratory and inflammatory medicine.

2. BRONCHIAL ASTHMA: PATHOPHYSIOLOGY, CLASSIFICATION, DIAGNOSIS, AND CURRENT THERAPEUTICS

2.1 Molecular and Cellular Pathophysiology

The pathogenesis of bronchial asthma is a highly orchestrated, multi-cellular process involving both innate and adaptive immune effector mechanisms operating in an anatomically complex mucosal microenvironment. The initiating event in atopic asthma involves inhalational exposure to specific allergens — house dust mite proteins, fungal spores, animal epithelia, or pollen — which are processed by airway epithelial cells and resident dendritic cells acting as professional antigen-presenting cells. Dendritic cells bearing processed allergen peptide-MHC class II complexes move to local lymph nodes, where they stimulate naïve CD4+ T-helper cells with IL-25, IL-33, and TSLP (thymic stromal lymphopoietin) to differentiate into Th2 cells. microenvironment generated by activated epithelial cells [11].

The defining characteristics of allergic asthma are orchestrated by polarized Th2 cells, which produce a distinctive cytokine profile that includes IL-4, IL-5, IL-9, and IL-13. IL-5 is the primary eosinophil growth, differentiation, and survival factor; IL-13 causes goblet cell metaplasia, airway mucus hypersecretion, and subepithelial fibrosis that contribute to airway remodeling; IL-9 promotes mast cell proliferation and IgE production [11,12]. IgE antibodies attach to mast cells' and basophils' high-affinity FcεRI receptors, making these effector cells more susceptible to allergens in the future. Upon re-exposure, the multivalent allergen's cross-linking of neighboring IgE molecules causes mast cell degranulation, which releases preformed mediators such histamine, tryptase, and heparin and promotes the

de novo production of prostaglandin D2 and cysteinyl leukotrienes (LTC4, LTD4, and LTE4) Factor that activates platelets. These mediators collectively produce the early asthmatic response: bronchoconstriction, mucosal edema, and increased mucus secretion within minutes of allergen challenge [12].

Eotaxin-1/-2 chemokines and IL-5 drive eosinophilic airway infiltration during the late asthmatic response, which happens 6–12 hours after allergen exposure. Eosinophils release major basic protein, eosinophil cationic protein, and eosinophil peroxidase, which damages epithelial cells and intensifies the inflammatory cascade. Concurrent structural alterations in the airways — Subepithelial fibrosis (caused by TGF-β), smooth muscle hypertrophy and hyperplasia, angiogenesis, and mucus gland hyperplasia are all collectively referred to as airway remodeling. These structural alterations contribute to irreversible airflow limitation in long-standing asthma and underlie the progressive decline in lung function observed in inadequately treated patients [13].

At the molecular regulatory level, The master regulator of inflammatory gene expression in asthma is the transcription factor NF-κB (Nuclear Factor kappa-light-chain enhancer of activated B cells), which drives the transcription of COX-2, iNOS, TNF-α, IL-1β, IL-6, chemokines (CXCL8, CCL11), adhesion molecules (ICAM-1, VCAM-1), and numerous other inflammatory mediators. The JAK- STAT pathway, particularly STAT6 (downstream of IL-4 and IL-13) and STAT5 (downstream of IL-2 and GM-CSF), also plays a critical role in sustaining Th2 inflammatory signaling. Mitogen-activated protein kinases (MAPK) — p38, ERK, and JNK — transduce extracellular inflammatory signals to nuclear transcriptional machinery, representing additional pharmacological targets of therapeutic interest [14].

2.2 Classification of Asthma

2.2.1 Phenotypic Classification

Contemporary asthma classification acknowledges the substantial heterogeneity of this condition, distinguishing clinically recognizable phenotypes based on trigger factors, onset characteristics, and associated comorbidities:

- **Allergic (Atopic) Asthma:** The most prevalent phenotype, typically presenting in childhood, associated with sensitization to common aeroallergens and increased levels of both total and allergen-specific blood IgE. Responds well to ICS and anti-IgE biologics.
- **Non-Allergic Asthma:** Occurs when IgE is not present-mediated sensitization; more common in adult-onset disease and may involve neutrophilic or paucigranulocytic airway inflammation. Often more difficult to treat.
- **Late-Onset Eosinophilic Asthma:** Adult-onset disease characterized by marked blood and airway eosinophilia, frequently severe, and sometimes comorbid with nasal polyposis and NSAID hypersensitivity (AERD). Responds to anti-IL-5 biologics.
- **Exercise-Induced Bronchoconstriction (EIB):** Transient airway narrowing triggered by strenuous physical activity, mediated by airway cooling and osmotic changes in the periciliary fluid layer, activating mast cells to release prostaglandins and leukotrienes.
- **Occupational Asthma:** Caused by workplace sensitizers (isocyanates, flour dust, latex) or irritants; accounts for 9–15% of adult-onset asthma and may be reversible if exposure is discontinued early.
- **Obesity-Related Asthma:** Associated with mechanical impairment of lung function and adipose tissue-derived systemic inflammation; frequently non-eosinophilic and corticosteroid-resistant.

2.2.2 Endotypic Classification (Biological Subtypes)

Beyond phenotypic descriptors, endotyping — the classification of asthma according to distinct pathobiological mechanisms — is increasingly guiding precision medicine approaches:

- **Type-2 High Endotype:** Defined by elevated airway and/or blood eosinophilia, elevated FeNO, and elevated serum total IgE. Driven by Th2/ILC2 axis activation and IL-4, IL-5, IL-13 overproduction. Represents approximately 50–70% of the asthma population and constitutes the primary target of currently approved biologic agents.
- **Type-2 Low Endotype:** Encompasses neutrophilic asthma (associated with Th17 responses and IL-17 production, air pollution, and obesity) and paucigranulocytic asthma (normal airway cellularity despite persistent symptoms). Characterized by relative steroid insensitivity and significant unmet therapeutic need.
- **AERD Endotype:** Aberrant arachidonic acid metabolism resulting in constitutive overproduction of cysteinyl leukotrienes and prostaglandin E2 deficiency. Pharmacologically responsive to leukotriene modifiers.

2.2.3 Severity-Based Clinical Classification (GINA 2023)

Table 1. Severity-based clinical classification of bronchial asthma per GINA 2023 guidelines [5]

Severity	Daytime Symptoms	Night Awakenings	FEV_1 (% Predicted)	SABA Requirement
Intermittent	< 2 days/week	≤ 2/month	≥ 80%	≤ 2 days/week
Mild Persistent	> 2 days/week	3–4/month	≥ 80%	> 2 days/week, not daily
Moderate Persistent	Daily	> 1/week	60–80%	Daily
Severe Persistent	Continuous	Frequent (nightly)	< 60%	Several times/day

2.3 Diagnostic Approach to Bronchial Asthma

Accurate diagnosis of asthma requires integration of clinical history, physical examination findings, and objective physiological testing. No single diagnostic criterion is pathognomonic; rather, the diagnosis rests on a constellation of characteristic features:

1. **Symptom Assessment:** Episodic wheeze, cough (particularly nocturnal), breathlessness, and chest tightness, with documented variability in severity and temporal association with recognized trigger exposures. Symptom variability — characterized by spontaneous or treatment-induced improvement and recurrence upon trigger re-exposure — is a characteristic that sets asthma apart from fixed obstructive disorders.
2. **Spirometry:** Demonstration of variable, reversible airflow obstruction. A post-bronchodilator increase in FEV1 ≥ 12% AND ≥ 200 mL from baseline is the accepted threshold for bronchodilator reversibility. The FEV1/FVC ratio below the lower limit of normal (LLN) confirms obstruction.
3. **Peak Expiratory Flow (PEF) Monitoring:** Diurnal PEF variability exceeding 10% (calculated as the amplitude divided by mean daily PEF) over ≥ 2 weeks of monitoring supports asthma diagnosis and is particularly useful in resource-limited settings lacking spirometry access.
4. **Bronchial Provocation Testing:** Methacholine, histamine, or mannitol challenge is employed when resting spirometry is normal, but there is still a lot of clinical concern. A PC20 methacholine ≤ 4 mg/mL confirms significant airway hyperresponsiveness.
5. **Fractional Exhaled Nitric Oxide (FeNO):** a non-invasive indicator of inflammation of the eosinophilic airways. Values ≥ 50 ppb strongly support Type-2 airway inflammation and predict corticosteroid responsiveness; values < 25 ppb argue against this endotype.
6. **Allergy Testing:** Skin prick testing or allergen-specific IgE quantification (ImmunoCAP) identifies sensitizing allergens in atopic patients, guiding allergen avoidance strategies and eligibility for allergen immunotherapy or anti-IgE biologic therapy.
7. **Arterial Blood Gas Analysis:** Reserved for acute severe exacerbations to assess respiratory failure; a normal or rising PaCO2 in the context of severe obstruction signals imminent ventilatory failure requiring urgent escalation.
8. **Chest Imaging and Blood Eosinophil Count:** Used to exclude alternative diagnoses (pneumonia, malignancy, cardiac failure) and to assess comorbid conditions; blood eosinophilia (≥ 300 cells/μL) supports Type-2 endotyping and influences biologic therapy selection.

2.4 Pharmacotherapy of Asthma: Conventional Approaches and Limitations

Table 2. Pharmacological agents used in asthma management: mechanisms of action and clinical limitations [5,6]

Drug Class	Representative Agents	Mechanism of Action	Key Limitations
Inhaled Corticosteroids (ICS)	Budesonide, Fluticasone propionate, Beclomethasone	GR-α nuclear translocation → suppression of AP-1, NF-κB; reduced cytokine transcription; decreased inflammatory cell recruitment	Oropharyngeal candidiasis, dysphonia; growth suppression in children; adrenal suppression at high doses
Short-Acting β2-Agonists (SABAs)	Salbutamol, Terbutaline	β2-adrenoceptor agonism → adenylyl cyclase activation → elevated cAMP → PKA activation → bronchial smooth muscle relaxation	Tachyphylaxis with overuse; cardiovascular stimulation; associated with increased mortality when used without ICS
Long-Acting β2-Agonists (LABAs)	Salmeterol, Formoterol	Sustained β2 receptor agonism; lipophilic anchoring in membrane → prolonged duration of action	Contraindicated as monotherapy; must be combined with ICS; potential masking of worsening control

Leukotriene Receptor Antagonists (LTRAs)	Montelukast, Zafirlukast	CysLT1 receptor competitive antagonism; blocks bronchoconstriction and mucus secretion mediated by LTC4, LTD4, LTE4	Modest efficacy vs ICS; neuropsychiatric adverse effects (FDA black box warning for montelukast, 2020)
Biologic Agents	Omalizumab, Mepolizumab,	Targeted neutralization of IgE, IL-5, IL-5Rα, or IL-	Very high cost; subcutaneous administration; restricted to
Drug Class	**Representative Agents**	**Mechanism of Action**	**Key Limitations**
	Benralizumab, Dupilumab	4Rα/IL-13Rα1; disruption of Type-2 inflammatory cascade	severe uncontrolled asthma; limited availability in LMIC
Methylxanthines	Theophylline, Aminophylline	Non-selective phosphodiesterase inhibition → elevated cAMP/cGMP; adenosine receptor antagonism; mild anti-inflammatory effects via histone deacetylase-2 activation	Narrow therapeutic index; multiple drug interactions (CYP1A2 substrate); requirement for serum level monitoring

3. INFLAMMATION: MOLECULAR PATHWAYS, CLASSIFICATIONS, AND THERAPEUTIC TARGETS

3.1 Cellular and Molecular Mechanisms of Inflammation Inflammation is a phylogenetically ancient, evolutionarily conserved biological response designed to contain and eliminate noxious stimuli — whether of infectious, traumatic, chemical, or immunological origin — and to initiate tissue repair. The cardinal macroscopic manifestations classically described as rubor (erythema), calor (local hyperthermia), tumor (edema), dolor (pain), and functio laesa (functional impairment) reflect a precisely coordinated sequence of vascular and cellular events at the microcirculatory level [15].

Pattern recognition is the first step in the molecular start of inflammation. A variety of germline- encoded pattern recognition receptors (PRRs), such as toll-like receptors (TLRs), NOD-like receptors (NLRs), RIG-I-like receptors (RLRs), and C-type lectin receptors, are expressed by tissue- resident macrophages and dendritic cells. These PRRs are able to identify both pathogen-associated molecular patterns (PAMPs) from invasive microorganisms and damage-associated molecular

patterns (DAMPs) released by damaged host cells. [15,16]. PRR engagement triggers signaling cascades converging on NF-κB — whose canonical activation involves IκB kinase (IKK)-mediated IκB inhibitory proteins are phosphorylated and broken down by proteases, allowing NF-κB dimers to go to the nucleus and activate the transcription of hundreds of pro-inflammatory genes.[16].

Simultaneously, phospholipase A2 (PLA2) liberates arachidonic acid from membrane phospholipids, which is then metabolized by cyclooxygenase (COX-1 and COX-2) enzymes into prostaglandins, thromboxanes, and prostacyclin, and by lipoxygenase (5-LOX) enzymes into leukotrienes and lipoxins. COX-2 expression is markedly induced by inflammatory stimuli via NF- κB activation, whereas COX-1 is constitutively expressed as a housekeeping enzyme. Prostaglandin E2 (PGE2) — a major COX product at inflammatory sites — sensitizes nociceptors and induces vasodilation and vascular permeability, accounting for the dolor and tumor of classical inflammation [17]. Leukotrienes, particularly LTB4 and the cysteinyl leukotrienes (LTC4, LTD4, LTE4), are powerful chemoattractants and bronchoconstricting agents, with pharmacological relevance extending across asthma, anaphylaxis, and allergic rhinitis [17].

It is now understood that the resolution of inflammation is not a passive termination of pro- inflammatory signals, but rather an active, molecularly designed process. Lipoxins (derived from arachidonic acid), resolvins (derived from EPA and DHA), proteins, and maresins are examples of specialized pro-resolving mediators (SPMs) that actively stop neutrophil influx, encourage macrophage phagocytosis of apoptotic cells (efferocytosis), and restore vascular and tissue homeostasis [18]. Chronic inflammation is increasingly thought to be caused by failure of resolution, which can be brought on by pharmacological, environmental, or genetic causes.

3.2 Classification of Inflammation

3.2.1 Acute Inflammation

Acute inflammation is a rapid-onset (seconds to minutes), self-limiting response characterized by:
(i) vascular dilation with increased blood flow (accounting for rubor and calor); (ii) increased microvascular permeability permitting protein-rich fluid exudation into the interstitium (producing tumor); (iii) emigration of leukocytes — predominantly neutrophils in the early phase — from microvessels to the tissue site; and (iv) local sensory nerve activation by bradykinin, histamine, and prostaglandins (producing dolor). In uncomplicated scenarios, acute inflammation resolves within days upon pathogen elimination and tissue repair,

mediated by change the synthesis of lipid mediators from pro-inflammatory to pro-resolving.

3.2.2 Chronic Inflammation

When the causative stimulus persists or when acute resolution fails, chronic inflammation ensues. Histologically characterized by the presence of mononuclear cells (activated macrophages, lymphocytes, plasma cells, and fibroblasts), chronic inflammation is associated with concurrent tissue destruction and attempted repair, frequently resulting in fibrosis and permanent structural distortion. Chronic inflammatory diseases — including asthma, COPD, rheumatoid arthritis, Crohn's disease, and systemic lupus erythematosus — collectively affect hundreds of millions of individuals globally and represent the primary factor in high-income nations' disability-adjusted life years [19].

3.3 Key Inflammatory Mediators and Their Pharmacological Relevance

Table 3. Major inflammatory mediators, their cellular sources, pharmacological actions, and corresponding therapeutic targets [16,17]

Mediator	Source	Principal Actions	Therapeutic Target
Histamine	Mast cells, basophils	Vasodilation, increased permeability, bronchoconstriction, pruritus	H1/H2 receptor antagonists; mast cell stabilizers
Prostaglandin E2 (PGE2)	Macrophages, fibroblasts, mast cells	Vasodilation, sensitization of pain receptors, fever, inhibition of Th1 responses	COX-1/COX-2 inhibitors (NSAIDs)
Mediator	**Source**	**Principal Actions**	**Therapeutic Target**
Leukotriene C4/D4	Mast cells, eosinophils	Potent bronchoconstriction, mucus secretion, eosinophil chemotaxis	CysLT1 receptor antagonists (montelukast)
TNF-α	Macrophages, mast cells, T-cells	Upregulation of adhesion molecules; NFκB activation; cachexia; endothelial activation	Anti-TNF biologics (infliximab, etanercept)
IL-4	Th2 lymphocytes, mast cells	IgE class switching; Th2 differentiation; VCAM-1 upregulation	Dupilumab (anti-IL-4Rα)
IL-5	Th2 lymphocytes, ILC2	Eosinophil production, differentiation, activation, and survival	Mepolizumab, benralizumab (anti-IL-5/IL-5Rα)
IL-13	Th2 lymphocytes, ILC2	Goblet cell metaplasia, mucus hypersecretion, subepithelial fibrosis	Tralokinumab (anti-IL-13); dupilumab
Reactive Oxygen Species	Neutrophils, macrophages, eosinophils	DNA damage, lipid peroxidation, protein oxidation, amplified NF-κB activation	Antioxidants (NAC, SOD mimetics); plant phenolics

3.4 Shared Etiopathogenic Risk Factors: Asthma and Systemic Inflammation

Epidemiological and mechanistic evidence supports the existence of shared environmental and host- derived risk factors that simultaneously predispose to both pulmonary and systemic inflammatory conditions:

9. **Tobacco Smoke Exposure:** Active and passive smoking promotes sustained oxidative stress, activates PRRs in airway epithelium and alveolar macrophages, and impairs glucocorticoid receptor function (through oxidant-mediated reduction of HDAC2 activity), contributing to corticosteroid-refractory inflammatory states. Smoking significantly worsens asthma control and accelerates lung function decline [20].
10. **Obesity and Metabolic Dysfunction:** In obese people, adipose tissue serves as an active endocrine organ secreting pro-inflammatory adipokines — leptin, resistin, and visfatin — while producing reduced quantities of the anti-inflammatory adipokine adiponectin. This adipokine imbalance generates low-grade systemic inflammation, exacerbates airway hyperresponsiveness, and promotes a non-eosinophilic asthma phenotype that responds poorly to ICS [20].
11. **Environmental Pollutants and Occupational Exposures:** Particulate matter (PM2.5, PM10), ozone, nitrogen dioxide, and heavy metals (lead, cadmium, arsenic) activate NLRP3 inflammasome complexes, promote oxidative epithelial injury, disrupt innate mucosal barrier function, and enhance immunological sensitization to allergens, contributing to asthma inception and

exacerbation [21].

12. **Microbiome Alterations:** Dysbiotic changes in the upper and lower respiratory tract microbiomes — characterized by reduced microbial diversity and expansion of pathobionts — dysregulate mucosal innate immune responses, lower the threshold for Th2 polarization, and promote IgE-mediated sensitization. The hygiene hypothesis and biodiversity hypothesis extend this concept to posit that reduced early-life microbial exposure impairs regulatory immune development, predisposing to allergic disease [22].
13. **Psychosocial Stress:** The hypothalamic-pituitary-adrenal (HPA) axis is dysregulated by long-term psychological stress, promoting glucocorticoid receptor insensitivity in immune cells and reducing endogenous anti-inflammatory cortisol signaling. Stress-induced norepinephrine release further activates NF-κB in mast cells and macrophages, amplifying inflammatory cytokine production and worsening asthma control [23].
14. **Genetic Predisposition:** Polymorphisms in the genes that encode IL-33, TSLP, IL-1RL1 (ST2), ORMDL3, GSDMB, and various HLA-DQ loci as asthma susceptibility determinants, highlighting the interplay between genetic architecture and environmental exposures in disease inception [24].

4. MEDICINAL PLANTS WITH DOCUMENTED ANTI-ASTHMATIC AND ANTI-INFLAMMATORY ACTIVITY: TAXONOMIC AND PHYTOCHEMICAL OVERVIEW

The following table (Table 4) provides a consolidated taxonomic, phytochemical, and pharmacological overview of the fifteen medicinal plants systematically reviewed in this article. Plant selection was guided by availability of peer-reviewed experimental and/or clinical data, ethnobotanical significance, and mechanistic pharmacological plausibility.

Table 4. Comprehensive phytochemical and pharmacological overview of medicinal plants with anti-asthmatic and anti-inflammatory activities.

No	Botanical Name	Commo n Name	Plant Part	Therapeutic Profile	Extract Type	Principal Bioactive Phytoconstituents
1	*Azadirachta indica A. Juss.*	Neem	Leaves, bark, seeds	Anti-inflammatory, antimicrobial, immunomodulatory, bronchodilator y	Ethanolic, aqueous	Azadirachtin, Nimbin, Nimbidin, Gedunin, Quercetin, Nimbolide, β-sitosterol, Nimbinene
2	*Carum copticum (L.) C.B.Clarke*	Ajwain / Bishop's Weed	Fruits (seeds)	Bronchodilatory, antispasmodic, anti-inflammatory, antifungal	Essential oil, aqueous boiled extract	Thymol (30–60%), Carvacrol, p- Cymene, γ-Terpinene, β-Pinene, Terpinen-4-ol
3	*Crocus sativus L.*	Saffron	Dried stigmas	Anti- asthmatic, antioxidant, immunomodulatory, mast cell stabilization	Hydroalcoholic extract, aqueous	Crocin, Crocetin, Safranal, Picrocrocin, Kaempferol, Quercetin
No	**Botanical Name**	**Commo n Name**	**Plant Part**	**Therapeutic Profile**	**Extract Type**	**Principal Bioactive Phytoconstituents**
4	*Mentha longifolia (L.) L.*	Wild Mint / Horse Mint	Leaves, aerial parts	Antispasmodic, antitussive, anti-inflammatory, mucolytic	Essential oil, ethanolic	Menthol, Menthone, Pulegone, Limonene, 1,8-Cineole, Rosmarinic acid
5	*Curcuma longa L.*	Turmeri c	Rhizome	Anti-inflammatory, antioxidant, immunomodulatory, anti-asthmatic, anticancer	Curcuminoid extract (ethanolic), CO2-supercritical	Curcumin, Demethoxycurcumin, Bisdemethoxycurcumin, ar- Turmerone, Zingiberene
6	*Olea europaea L.*	Olive	Fruit, leaves	Cardioprotective, anti-	Olive oil, leaf hydroethanolic	Oleuropein, Hydroxytyrosol, Oleocanthal, Oleic acid,

				inflammatory, antioxidant, antihypertensi ve	extract	Oleanolic acid, Apigenin
7	*Ocimum sanctum L.*	Tulsi / Holy Basil	Leaves, seeds	Adaptogenic, anti-asthmatic, antimicrobial, immunomodul atory, antidiabetic	Ethanolic, essential oil, fixed oil	Eugenol, Ursolic acid, Rosmarinic acid, β-Caryophyllene, Linalool, Ocimarin, Circineol
8	*Glycyrrhiza glabra L.*	Licorice / Sweetw ood	Root and rhizome	Expectorant, anti-inflammatory, antiviral, anti-ulcer, mast cell stabilization	Aqueous, hydroalcoho lic, standardize d glycyrrhizin extract	Glycyrrhizin, Glycyrrhizinic acid, Glabridin, Liquiritin, Isoliquiritigenin, 18β-Glycyrrhetinic acid
9	*Zingiber officinale Roscoe*	Ginger	Rhizome	Anti-inflammatory, bronchodilator y, antiemetic, antioxidant	Oleoresin, ethanolic extract, fresh juice	[6]-Gingerol, [8]-Gingerol, [6]- Shogaol, Zingerone, Paradol, β-Sesquiphellandrene
10	*Achyranthes aspera L.*	Devil's Horsew hip	Whole plant, root	Anti- asthmatic, mast cell stabilization, hepatoprotecti ve, diuretic	Methanolic, petroleum ether, aqueous	Saponins (achyranthine), Ecdysterone, Oleanolic acid, Triterpenoids, Alkaloids, Betaine
11	*Allium cepa L.*	Onion	Bulb	Anti-asthmatic, anti-allergic, bronchodilator y, antimicrobial	Aqueous, ethanolic	Quercetin, Allicin, Kaempferol, Dipropyl disulfide, Cyanidin-3-glucoside, Fisetin
No	**Botanical Name**	**Commo n Name**	**Plant Part**	**Therapeutic Profile**	**Extract Type**	**Principal Bioactive Phytoconstituents**
12	*Nigella sativa L.*	Black Seed / Kalonji	Seeds	Anti- asthmatic, antioxidant, immunomodul atory, anticancer, antimicrobial	Fixed oil, essential oil, ethanolic	Thymoquinone, Nigellone, α-Hederin, Carvacrol, Thymol, Dithymoquinone, Nigellidine
13	*Ephedra gerardiana Wall.*	Somlata / Pakistan i Ephedra	Aerial stems	Bronchodilato ry, decongestant, anti-inflammatory, CNS stimulant	Alkaloidal extract, aqueous	Ephedrine, Pseudoephedrine, Methylephedrine, Norpseudoephedrine, Ephedroxane, Tannins
14	*Eucalyptus globulus Labill.*	Blue Gum Eucalyp tus	Leaves	Expectorant, bronchodilator y, antiseptic, anti-inflammatory, mucolytic	Essential oil	1,8-Cineole (Eucalyptol, 60–85%), α- Pinene, Globulol, α-Eudesmol, β- Eudesmol, Cis-sabinol
15	*Picrorhiza kurroa Royle ex Benth.*	Kutki / Karoo	Rhizome and roots	Anti- asthmatic, immunomodul atory, hepatoprotecti ve, antioxidant	Methanolic, aqueous	Picroside I, Picroside II, Kutkin, Kutkoside, Apocynin, Veronicoside, Androsin, Catalpol

5. DETAILED PHARMACOLOGICAL PROFILES OF REVIEWED MEDICINAL PLANTS

5.1 Azadirachta indica A. Juss. (Neem)

Botanical classification and ethnopharmacological background: Native to the Indian subcontinent, Azadirachta indica is a fast-growing evergreen tree that has spread throughout tropical and subtropical Africa and Asia. It belongs to the Meliaceae family. In the Ayurvedic materia medica, the tree occupies a position of singular pharmacological versatility — virtually all

anatomical parts (bark, leaves, seeds, roots, flowers, and fruit pulp) are documented as medicinal materials for diverse indications spanning dermatological, hepatic, antimicrobial, antifertility, and anti-inflammatory applications [25]. The tree is colloquially referred to as the "village pharmacy" in South Asian ethnomedicinal traditions.

5.2 Carum copticum (L.) C.B.Clarke (Ajwain / Bishop's Weed)

Botanical and ethnobotanical background: Carum copticum — commonly designated Ajwain, Bishop's Weed, or Ajowan caraway — is an annual herbaceous plant of the Apiaceae family widely cultivated throughout the Indian subcontinent, Iran, Egypt, and Afghanistan. The fruits (commonly termed 'seeds') have occupied a central position in traditional Ayurvedic and Unani pharmacopeias as carminative, antispasmodic, and bronchodilatory agents, with documented use in the management of asthma, chronic bronchitis, and spasmodic coughs extending over several millennia [28].

5.3 Crocus sativus L. (Saffron)

Botanical and ethnopharmacological context: Crocus sativus, a stemless perennial geophyte belonging to the Iridaceae family, is cultivated primarily in Iran, Spain, India (Kashmir), Greece, and Morocco for its aromatic dried stigmas — saffron — which constitute the world's most expensive spice by weight. In Persian (Unani) medicine, saffron has been employed as a bronchodilator, anti-depressant, aphrodisiac, and tonic for over 3,500 years, with references appearing in texts attributed to Avicenna (Ibn Sina). Modern pharmacological investigations have identified multiple mechanisms underlying its documented pharmacological activities [30].

5.4 Mentha longifolia (L.) L. (Wild Mint)

Botanical profile and traditional use: Mentha longifolia (horse mint or wild mint) belongs to the Lamiaceae family and is distributed across Europe, Asia, and northern Africa. The species is distinguished from cultivated mint varieties by its characteristically woolly gray-green leaves and more pungent aroma profile. In Greco-Arabic and South Asian traditional medicine systems, M. longifolia preparations — typically as infusions, essential oil inhalations, or topical poultices — have been prescribed for respiratory complaints including bronchospasm, productive cough, and pleuritic pain. The plant is classified in Unani medicine as possessing a warm, dry temperament (Mizaj) conducive to bronchodilation and expectoration [33].

5.5 Curcuma longa L. (Turmeric)

Botanical description and historical context: Curcuma longa, a perennial rhizomatous monocot belonging to the Zingiberaceae family, is indigenous to South and Southeast Asia where it has been cultivated continuously for over 4,000 years. Its use as a medicinal, culinary, and ritual agent is documented across Ayurvedic, Traditional Chinese Medicine, and Southeast Asian healing traditions. The rhizome — when dried and powdered — yields the culinary spice turmeric, whose characteristic golden-yellow color derives from its principal curcuminoid constituents. C. longa currently ranks among the most extensively researched medicinal plants in the biomedical literature, with over 10,000 peer-reviewed publications archived in PubMed as of 2024 [35].

5.6 Olea europaea L. (Olive)

Botanical and ethnopharmacological profile: Olea europaea, the cultivated olive, is a long-lived evergreen tree belonging to the Oleaceae family and native to the Mediterranean basin, where it has been cultivated for at least 6,000 years. Beyond its culinary and economic significance, O. europaea occupies a prominent position in the Mediterranean traditional pharmacopoeia, with olive oil, leaf

preparations, and bark decoctions documented for the management of hypertension, diabetes mellitus, gastrointestinal disorders, and inflammatory conditions. The Mediterranean dietary pattern

— characterized by high olive oil consumption — has been epidemiologically associated with reduced incidence of cardiovascular disease, certain cancers, neurodegenerative disorders, and inflammatory conditions [39].

5.7 Ocimum sanctum L. (Tulsi / Holy Basil)

Taxonomy and traditional significance: Ocimum sanctum Linn. (syn. Ocimum tenuiflorum), a perennial aromatic herb of the Lamiaceae family, holds unique cultural and religious significance in Hindu tradition as a sacred plant (Tulasi), cultivated in virtually every household across the Indian subcontinent. In Ayurvedic medicine, it is classified as a rasayana (rejuvenative), medhya (nootropic), and adaptogen, prescribed for an exceptionally broad range of conditions including fever, respiratory ailments (kasa — cough; shwasa — asthma), skin disorders, and infectious diseases. Pharmacological investigations over the past five decades have substantiated many of these traditional applications through rigorous experimental evidence [42].

5.8 Glycyrrhiza glabra L. (Licorice / Sweetwood)

Botanical and ethnopharmacological background: Glycyrrhiza glabra — licorice — is a perennial leguminous herb of the Fabaceae family native to the Mediterranean basin and Southwest Asia, extensively cultivated across China, Iran, Russia, and Spain. Among the most ancient medicinal plants in recorded history, G. glabra preparations appear in Egyptian papyri dating to 1500 BCE, and the plant is documented in the ancient Greek, Roman, Chinese (Gan Cao), and Ayurvedic

pharmacopeias. Its primary indications across these systems include respiratory disorders (cough, asthma, laryngitis), gastrointestinal conditions (peptic ulcer, inflammatory bowel disease), and liver

diseases — all conditions subsequently validated to involve inflammatory mechanisms susceptible to glycyrrhizin modulation [46].

5.9 Zingiber officinale Roscoe (Ginger)

Botanical identity and traditional therapeutic context: Zingiber officinale, a perennial monocot belonging to the Zingiberaceae family, is native to tropical Southeast Asia and has been cultivated for culinary and medicinal purposes for over 5,000 years. The plant's fresh and dried rhizomes constitute major components of traditional Asian and Middle Eastern medicine pharmacopeias, prescribed for diverse indications including nausea and vomiting (in pregnancy, chemotherapy, and postoperatively — among the best-documented herbal effects), pain management, digestive disorders, and inflammatory conditions. Ginger is mentioned in Ayurvedic texts as a universal medicine (vishwabhesaj) with warming, carminative, and anti-inflammatory properties [49].

5.10 Achyranthes aspera L. (Devil's Horsewhip / Prickly Chaff Flower)

Botanical and ethnobotanical background: Achyranthes aspera — variously known as Devil's Horsewhip, Prickly Chaff Flower, or Chirchira in Hindi — is an erect annual or perennial herb of the Amaranthaceae family distributed across tropical and subtropical regions of Asia, Africa, and the Americas. The plant holds extensive ethnomedicinal recognition across South Asian traditional systems, with documented applications in the management of asthma, bronchitis, kidney stones, skin disorders, fever, and snake envenomation. In Ayurvedic medicine, the plant — referred to as Apamarga — is classified as a dipana (digestive stimulant) and shodhana (purificatory) agent with additional respiratory therapeutic applications [52].

5.11 Allium cepa L. (Onion)

Botanical description and dietary-medicinal duality: Allium cepa, a bulbous biennial of the Amaryllidaceae family (formerly Alliaceae), has been cultivated as both a dietary staple and medicinal plant for at least 5,000 years, with documentation of its therapeutic use in ancient Egyptian, Greek, Roman, and Indian civilizations. In traditional medicine systems, onion preparations have been employed for respiratory conditions (cough, asthma, bronchitis), cardiovascular disease prevention, and antimicrobial applications. The epidemiological evidence supporting its health benefits is substantial — prospective cohort studies report inverse associations between flavonoid-rich food intake (including onions) and risk of asthma, COPD, and cardiovascular events [54].

5.12 Nigella sativa L. (Black Seed / Kalonji)

Ethnopharmacological significance and botanical background: Nigella sativa, an annual flowering plant of the Ranunculaceae family indigenous to Southwest Asia and the Mediterranean basin, produces seeds that have occupied a position of unparalleled importance in Islamic traditional medicine since the 7th century CE. The prophetic tradition attributing therapeutic value to black seed for 'every disease except death' reflects the extraordinarily broad pharmacological spectrum of this plant, which modern pharmacological investigations have increasingly substantiated. The plant is cultivated extensively across the Middle East, North Africa, South Asia, and increasingly in Europe, primarily for its pharmacologically active seeds [57].

5.13 Ephedra gerardiana Wall. ex Meisn. (Somlata / Pakistani Ephedra)

Botanical classification and historical pharmacological importance: Ephedra gerardiana, a leafless jointed shrub of the Ephedraceae family distributed across the high-altitude regions of Pakistan, Afghanistan, and the Himalayan ranges of India, belongs to the genus that produced one

of the most historically significant contributions to respiratory pharmacology. The alkaloid ephedrine — isolated from Chinese Ephedra sinica (Ma Huang) in 1887 — preceded synthetic bronchodilators by decades and served as the primary pharmacological reference for subsequent development of salbutamol and other selective β2-agonists. Ephedra preparations have been employed in traditional Chinese medicine (as Ma Huang) and in Tibetan and Unani systems for asthma, bronchitis, rhinitis, and anaphylaxis management for over 5,000 years [61].

5.14 Eucalyptus globulus Labill. (Blue Gum / Tasmanian Bluegum)

Botanical profile and global pharmacological relevance: Eucalyptus globulus, a fast-growing evergreen tree native to southeastern Australia and Tasmania, is among the most widely planted exotic tree species globally, cultivated across the Mediterranean basin, China, India, South America, and sub-Saharan Africa for timber, paper pulp, and essential oil production. The essential oil distilled from its mature leaves is one of the highest-production volume botanical essential oils worldwide, with documented applications spanning respiratory medicine, dentistry, dermatology, and veterinary practice across multiple continents and traditional systems [64].

5.15 Picrorhiza kurroa Royle ex Benth. (Kutki / Karoo)

Botanical identity and conservation status: Picrorhiza kurroa is a small perennial alpine herb belonging to the Plantaginaceae family (formerly Scrophulariaceae), native to the Himalayan mountain ranges of India, Nepal, and Pakistan, growing at altitudes of 3,000–5,000

meters above sea level. The plant is harvested primarily for its bitter rhizome and roots, which constitute the pharmacologically active portion employed in Ayurvedic medicine (as Katuki or Kutki) and Tibetan medicine. Due to unsustainable wild harvesting driven by high commercial demand, P. kurroa has been designated a Schedule VI threatened species under India's Wildlife Protection Act, making conservation and cultivation a parallel research priority alongside pharmacological investigation [68].

6. COMPARATIVE ANALYSIS OF PHYTOCHEMICAL VS. CONVENTIONAL DRUG MECHANISMS

A mechanistic comparison of herbal phytoconstituents with conventional anti-asthmatic and anti- inflammatory drugs reveals both points of convergence — validating the pharmacological rationale for herbal therapies — and distinct mechanistic features that may confer complementary or superior profiles in specific contexts.

Table 5. Comparative mechanistic analysis of herbal phytoconstituents and conventional pharmacological agents across key anti-asthmatic and anti-inflammatory molecular targets.

Target / Pathway	Conventional Agent	Herbal Phytoconstituent	Source Plant	Evidence Level
NF-κB inhibition	Dexamethasone (indirect)	Curcumin, Nimbolide, Thymoquinone, Oleuropein	*C. longa / A. indica / N. sativa / O. europaea*	Preclinical (strong); Clinical (moderate)
COX-2 inhibition	Celecoxib, Ibuprofen	Curcumin, Eugenol, Oleocanthal, Thymoquinone	*C. longa / O. sanctum / O. europaea / N. sativa*	Preclinical (strong); Clinical (emerging)
5-LOX inhibition	Zileuton	Quercetin, Ursolic acid, 18β-Glycyrrhetinic acid, TQ	*A. cepa / O. sanctum / G. glabra / N. sativa*	Preclinical (strong); Clinical (limited)
Mast cell stabilization	Sodium cromoglicate	Quercetin, Fixed oil of O. sanctum, N. sativa extract	*A. cepa / O. sanctum / N. sativa*	Preclinical (moderate); Clinical (limited)
β2-adrenoceptor agonism	Salbutamol, Formoterol	Ephedrine, Pseudoephedrine	*E. gerardiana*	Clinical (established)
PDE4 inhibition	Roflumilast	[6]-Gingerol, [6]-Shogaol	*Z. officinale*	Preclinical (moderate)
H1 receptor antagonism	Cetirizine, Loratadine	Nigellone, Quercetin, Safranal	*N. sativa / A. cepa / C. sativus*	Preclinical (moderate)
NADPH oxidase inhibition	NAC (indirect)	Apocynin	*P. kurroa*	Preclinical (strong)
IL-5 / eosinophil suppression	Mepolizumab (anti-IL-5)	TQ, Crocin, Safranal	*N. sativa / C. sativus*	Preclinical (strong)
Mucokinesis / expectorant	Ambroxol, ACC	1,8-Cineole (Eucalyptol), Glycyrrhizin saponins	*E. globulus / G. glabra*	Clinical (established)

This comparison highlights that several herbal phytoconstituents engage with the same validated pharmacological targets as established drugs — providing mechanistic credibility — while also demonstrating unique features such as simultaneous COX and 5-LOX inhibition (curcumin, gingerols) that are difficult to achieve with conventional NSAIDs without sacrificing selectivity. The multi-target nature of plant extracts — wherein multiple constituents act on complementary targets simultaneously — represents a biological systems pharmacology approach that may be particularly suited to the mechanistic complexity of chronic inflammatory diseases.

7. RATIONALE FOR PHYTOTHERAPEUTIC INTEGRATION IN ASTHMA AND INFLAMMATORY DISEASE MANAGEMENT

7.1 Pharmacoeconomic Considerations

The economic burden of asthma and chronic inflammatory diseases is substantial: global annual direct healthcare costs attributable to asthma are estimated to exceed USD 80 billion, with indirect costs from lost productivity adding substantially to this figure. Biologic agents targeting specific inflammatory pathways — while therapeutically transformative in severe disease — carry annual treatment costs of USD 15,000–30,000 per patient, effectively precluding their use in the majority of the world's asthmatic population. Plant-derived preparations, particularly those derived from indigenous species cultivated locally, represent dramatically more cost-accessible therapeutic options — a consideration of paramount importance in low- and middle-income countries where the burden of asthma mortality is greatest [7,8].

7.2 Pharmacological Advantages: Multi-Target Activity in Complex Diseases

Asthma and chronic inflammation are pathophysiologically complex conditions involving multiple simultaneously dysregulated molecular pathways. The conventional pharmaceutical paradigm of single-target, highly selective drugs — while offering advantages in terms of predictable pharmacokinetics and precise mechanism-of-action characterization — may be inherently limited in its capacity to address this biological complexity. Plant extracts, by virtue of their chemical diversity, engage multiple relevant targets simultaneously: as illustrated by curcumin inhibiting NF-κB, COX- 2, 5-LOX, and Nrf2 simultaneously; or by N. sativa constituents reducing leukotriene synthesis (thymoquinone via 5-LOX inhibition), suppressing Th2 cytokines (TQ via GATA-3 inhibition), stabilizing mast cells (α-hederin), and scavenging ROS (TQ via Nrf2 activation). This systems pharmacology approach may confer advantages in managing the redundant and mutually compensatory signaling networks characteristic of chronic inflammatory states [72].

7.3 Safety Profile Considerations

A critical appraisal of the safety profile of herbal anti-asthmatic and anti-inflammatory agents is essential, and requires acknowledgment of both potential advantages and genuine risks. Many phytochemicals at typical therapeutic concentrations demonstrate favorable acute safety profiles, with centuries of traditional use providing empirical evidence of tolerability at conventional doses. Several compounds (notably curcumin, quercetin, rosmarinic acid) have been designated as GRAS (Generally Recognized As Safe) by regulatory authorities. However, the assumption that 'natural' equates to 'safe' is pharmacologically unfounded: ephedrine-containing preparations carry genuine cardiovascular risks; licorice glycyrrhizin causes pseudohyperaldosteronism with hypokalemia and hypertension at high doses (>100 mg/day); pulegone in mint oils is hepatotoxic at excessive doses; and pyrrolizidine alkaloids in certain Symphytum species cause hepatic veno-occlusive disease [73]. Additionally, herb-drug interactions mediated by cytochrome P450 modulation (St. John's Wort

being the most documented example, but applicable to other herbs) can significantly alter plasma concentrations of co-administered conventional medications. Rigorous safety evaluation — including genotoxicity, reproductive toxicity, and pharmacokinetic interaction studies — is therefore an essential component of any herbal therapeutic development program [73].

7.4 Standardization and Quality Control Imperatives

A persistent challenge in phytotherapy research and clinical application is the enormous variability in phytochemical composition of plant materials and preparations — arising from variations in plant genetics, geographic origin, agricultural practices, harvesting season, post-harvest processing, and storage conditions. Without adequate standardization to defined content of key active constituents, clinical trial results are not reproducible and dose-response relationships cannot be established. Best practices for standardization include: (i) authentication of plant material by trained botanists and molecular (DNA barcoding) methods; (ii) quantitative phytochemical profiling by validated HPLC-UV/DAD, LC-MS/MS, or GC-MS methods; (iii) specification of minimum active constituent content in standardized extracts; (iv) Good Agricultural and Collection Practices (GACP) at the primary production level; and (v) Good Manufacturing Practices (GMP) throughout extraction and formulation. Regulatory frameworks such as those established by the European Medicines Agency (EMA) Committee on Herbal Medicinal Products (HMPC), the U.S. Pharmacopeia (USP), and the Ayurvedic Pharmacopoeia of India (API) provide frameworks for quality standards that should be adopted in research settings [74].

9. CONCLUSION

This comprehensive review has synthesized and critically evaluated the pharmacological evidence supporting the anti-asthmatic and anti-inflammatory properties of fifteen pharmacologically significant medicinal plants across multiple chemical classes and mechanistic categories. The reviewed agents collectively engage with virtually every major validated molecular target in asthma and inflammatory pathophysiology — including NF-κB, AP-1, COX-2, 5-LOX, mast cell FcεRI signaling, Th2 cytokine networks, bronchial β2-adrenoceptors, and NADPH oxidase — providing a mechanistically coherent scientific foundation for their traditional and contemporary therapeutic applications.

Several plants have accumulated particularly robust evidence bases that extend from precise molecular characterization to preclinical efficacy demonstration and — in selected cases — confirmation through clinical trials: Nigella sativa (supported by multiple randomized controlled trials demonstrating significant spirometric improvements and symptomatic benefit in asthmatic patients), Eucalyptus globulus (with clinical evidence for corticosteroid-sparing effects via oral 1,8- cineole supplementation), Curcuma longa (supported by mechanistic breadth and multiple clinical trials in inflammatory conditions, with asthma-specific data emerging), and Carum copticum (demonstrating clinically meaningful bronchodilatory effects comparable to theophylline in a controlled human study). These plants represent priority candidates for further clinical development.

The overarching scientific imperative emerging from this review is the urgent need for standardized, well-powered, methodologically rigorous clinical trials — conducted using authenticated, characterized, and quantitatively standardized herbal preparations — in appropriately phenotyped patient populations. The field has advanced substantially from its ethnobotanical foundations toward mechanistic pharmacological characterization; the next essential developmental stage requires equivalent rigor in clinical evaluation. Concurrently, issues of

standardization, pharmacokinetics, drug interaction profiling, and long-term safety monitoring must be systematically addressed to support evidence-based clinical integration.

Phytotherapy does not represent a wholesale alternative to evidence-based conventional pharmacotherapy — particularly in patients with severe or life-threatening asthma where proven therapies are available. Rather, it represents a scientifically credible complement: potentially offering cost-effective adjunctive options, mechanistically distinct approaches for patients with treatment-refractory phenotypes, and culturally concordant primary care options in regions where conventional medicines remain inaccessible. Realizing this potential in a manner that honors both traditional knowledge and contemporary scientific rigor constitutes a compelling intellectual and clinical challenge for the global biomedical research community.

REFERENCES

1. World Health Organization. (2023). *Asthma fact sheet*. https://www.who.int/news-room/fact-sheets/detail/asthma
2. National Institutes of Health, & National Heart, Lung, and Blood Institute. (1997). *Guidelines for the diagnosis and management of asthma* (NIH Publication No. 97-4051).
3. Medzhitov, R. (2008). Origin and physiological roles of inflammation. *Nature, 454*(7203), 428–435. https://doi.org/10.1038/nature07201
4. Barnes, P. J. (2008). Immunology of asthma and chronic obstructive pulmonary disease. *Nature Reviews Immunology, 8*(3), 183–192. https://doi.org/10.1038/nri2254
5. Global Initiative for Asthma. (2023). *Global strategy for asthma management and prevention (2023 update)*. https://ginasthma.org
6. Reddel, H. K., Bacharier, L. B., Bateman, E. D., Brightling, C. E., Brusselle, G. G., Buhl, R., ... Oppenheimer, J. (2022). Global Initiative for Asthma strategy 2021: Executive summary and rationale for key changes. *Journal of Allergy and Clinical Immunology, 149*(6), 1730–1747. https://doi.org/10.1016/j.jaci.2021.10.003
7. Fabricant, D. S., & Farnsworth, N. R. (2001). The value of plants used in traditional medicine for drug discovery. *Environmental Health Perspectives, 109*(Suppl 1), 69–75. https://doi.org/10.1289/ehp.01109s169
8. World Health Organization. (2019). *WHO global report on traditional and complementary medicine 2019*.
9. Middleton, E., Jr., Kandaswami, C., & Theoharides, T. C. (2000). The effects of plant flavonoids on mammalian cells: Implications for inflammation, heart disease, and cancer. *Pharmacological Reviews, 52*(4), 673–751.
10. Calixto, J. B., Campos, M. M., Otuki, M. F., & Santos, A. R. S. (2004). Anti-inflammatory compounds of plant origin. *Planta Medica, 70*(2), 93–103. https://doi.org/10.1055/s-2004-815483
11. Lambrecht, B. N., & Hammad, H. (2015). The immunology of asthma. *Nature Immunology, 16*(1), 45–56. https://doi.org/10.1038/ni.3049
12. Holgate, S. T. (2012). Innate and adaptive immune responses in asthma. *Nature Medicine, 18*(5), 673–683. https://doi.org/10.1038/nm.2731
13. Bergeron, C., & Boulet, L. P. (2006). Structural changes in airway diseases: Characteristics, mechanisms, consequences, and pharmacologic modulation. *Chest, 129*(4), 1068–1087. https://doi.org/10.1378/chest.129.4.1068
14. Ito, K., Chung, K. F., & Adcock, I. M. (2006). Update on glucocorticoid action and resistance. *Journal of Allergy and Clinical Immunology, 117*(3), 522–543. https://doi.org/10.1016/j.jaci.2006.01.032
15. Kumar, V., Abbas, A. K., & Aster, J. C. (2020). *Robbins & Cotran pathologic basis of disease* (10th ed.). Elsevier.
16. Takeuchi, O., & Akira, S. (2010). Pattern recognition receptors and inflammation. *Cell, 140*(6), 805–820. https://doi.org/10.1016/j.cell.2010.01.022
17. Funk, C. D. (2001). Prostaglandins and leukotrienes: Advances in eicosanoid biology. *Science, 294*(5548), 1871–1875. https://doi.org/10.1126/science.294.5548.1871
18. Serhan, C. N. (2014). Pro-resolving lipid mediators are leads for resolution physiology. *Nature, 510*(7503), 92–101. https://doi.org/10.1038/nature13479
19. GBD 2019 Diseases and Injuries Collaborators. (2020). Global burden of 369 diseases and injuries in 204 countries and territories, 1990–2019. *The Lancet, 396*(10258), 1204–1222. https://doi.org/10.1016/S0140-6736(20)30925-9
20. Baffi, C. W., Wood, L., Winnica, D., Strollo, P. J., Jr., Gladwin, M. T., Que, L. G., & Holguin, F. (2017). Metabolic syndrome and the lung. *Chest, 151*(1), 198–213. https://doi.org/10.1016/j.chest.2016.08.1439
21. Kelly, F. J., & Fussell, J. C. (2015). Air pollution and public health: Emerging hazards and improved understanding of risk. *Environmental Geochemistry and Health, 37*(4), 631–649. https://doi.org/10.1007/s10653-015-9720-1

22. Arrieta, M. C., Stiemsma, L. T., Dimitriu, P. A., Thorson, L., Russell, S., Yurist-Doutsch, S., ... Finlay, B. B. (2015). Early infancy microbial and metabolic alterations affect risk of childhood asthma. *Science Translational Medicine, 7*(307), 307ra152. https://doi.org/10.1126/scitranslmed.aab2271

23. Chen, E., Miller, G. E., Shalowitz, M. U., Story, R. E., Strunk, R. C., & Pitts, S. (2019). Difficult family relationships, residential mobility, and asthma. *Pediatrics, 125*(3), e511–e518. https://doi.org/10.1542/peds.2009-0613

24. Ober, C., & Yao, T. C. (2011). The genetics of asthma and allergic disease: A 21st century perspective. *Immunological Reviews, 242*(1), 10–30. https://doi.org/10.1111/j.1600-065X.2011.01029.x

25. Biswas, K., Chattopadhyay, I., Banerjee, R. K., & Bandyopadhyay, U. (2002). Biological activities and medicinal properties of neem (*Azadirachta indica*). *Current Science, 82*(11), 1336–1345.

26. Gupta, S. C., Prasad, S., Reuter, S., Kannappan, R., Yadav, V. R., Bhatt, I. D., ... Aggarwal, B. B. (2011). Modification of cysteine 179 of IκBα kinase by nimbolide leads to down-regulation of NF-κB-regulated proteins. *Journal of Biological Chemistry, 286*(6), 4309–4318. https://doi.org/10.1074/jbc.M110.161984

27. Subapriya, R., & Nagini, S. (2005). Medicinal properties of neem leaves: A review. *Current Medicinal Chemistry – Anti-Cancer Agents, 5*(2), 149–156. https://doi.org/10.2174/1568011053174828

28. Morsi, N. M. (2000). Antimicrobial effect of crude extracts of *Nigella sativa* on multiple antibiotics-resistant bacteria. *Acta Microbiologica Polonica, 49*(1), 63–74.

29. Boskabady, M. H., Jandaghi, P., Kiani, S., & Hasanzadeh, L. (2004). Antiasthmatic effect of *Carum copticum* in airways of asthmatic patients. *Journal of Ethnopharmacology, 95*(2–3), 369–374. https://doi.org/10.1016/j.jep.2004.08.016

30. Hosseinzadeh, H., & Nassiri-Asl, M. (2013). Avicenna's *Canon of Medicine* and saffron (*Crocus sativus*): A review. *Phytotherapy Research, 27*(4), 475–483. https://doi.org/10.1002/ptr.4784

31. Mahmoudabady, M., Neamati, A., Vosooghi, S., Aghababa, H., & Shahraki, S. (2013). Hydroalcoholic extract of *Crocus sativus* effects on bronchial inflammatory cells in ovalbumin-sensitized rats. *Avicenna Journal of Phytomedicine, 3*(4), 356–363.

32. Gholamnezhad, Z., Keyhanmanesh, R., & Boskabady, M. H. (2015). Anti-inflammatory, antioxidant, and immunomodulatory aspects of *Crocus sativus* for the treatment of asthma. *Drug Research, 65*(12), 684–692. https://doi.org/10.1055/s-0034-1394615

33. Mossaheb, N., & Nater, U. M. (2022). Evaluation of *Mentha* species for antitussive and antiasthmatic potential: A systematic review. *Journal of Ethnopharmacology, 287*, 114914. https://doi.org/10.1016/j.jep.2021.114914

34. Nair, M. G., Bhowmik, D., & Kumar, K. P. S. (2012). *Mentha piperita* (peppermint): An overview. *Journal of Pharmaceutical and Phytochemical Research, 1*(1), 1–6.

35. Aggarwal, B. B., & Harikumar, K. B. (2009). Potential therapeutic effects of curcumin. *International Journal of Biochemistry & Cell Biology, 41*(1), 40–59. https://doi.org/10.1016/j.biocel.2008.06.010

36. Gupta, S. C., Patchva, S., & Aggarwal, B. B. (2013). Therapeutic roles of curcumin. *AAPS Journal, 15*(1), 195–218. https://doi.org/10.1208/s12248-012-9432-8

37. Panahi, Y., Khalili, N., Hosseini, M. S., Abbasinazari, M., & Sahebkar, A. (2014). Lipid-modifying effects of curcuminoids-piperine combination. *Phytomedicine, 21*(13), 1694–1700. https://doi.org/10.1016/j.phymed.2014.08.005

38. Anand, P., Kunnumakkara, A. B., Newman, R. A., & Aggarwal, B. B. (2007). Bioavailability of curcumin. *Molecular Pharmaceutics, 4*(6), 807–818. https://doi.org/10.1021/mp700113r

39. Covas, M. I., Nyyssönen, K., Poulsen, H. E., Kaikkonen, J., Zunft, H. J. F., Kiesewetter, H., ... Marrugat, J. (2006). Polyphenols in olive oil and heart disease risk. *Annals of Internal Medicine, 145*(5), 333–341. https://doi.org/10.7326/0003-4819-145-5-200609050-00006

40. Beauchamp, G. K., Keast, R. S. J., Morel, D., Lin, J., Pika, J., Han, Q., ... Breslin, P. A. S. (2005). Ibuprofen-like activity in olive oil. *Nature, 437*(7055), 45–46. https://doi.org/10.1038/437045a

41. Millman, J., Okamoto, S., Kimura, M., Ueda, K., & Shimada, K. (2021). Oleuropein in olive leaf. *Nutrients, 13*(7), 2218. https://doi.org/10.3390/nu13072218

42. Kelm, M. A., Nair, M. G., Strasburg, G. M., & DeWitt, D. L. (2000). Phenolics from *Ocimum sanctum*. *Phytomedicine, 7*(1), 7–13. https://doi.org/10.1016/S0944-7113(00)80015-X

43. Prakash, P., & Gupta, N. (2005). Therapeutic uses of *Ocimum sanctum*. *Indian Journal of Physiology and Pharmacology, 49*(2), 125–131.

44. Singh, S., & Majumdar, D. K. (1997). Anti-inflammatory activity of *Ocimum sanctum*. *Indian Journal of Experimental Biology, 35*(4), 380–383.

45. Mondal, S., Mirdha, B. R., & Mahapatra, S. C. (2009). Science behind sacredness of Tulsi. *Indian Journal of Physiology and Pharmacology, 53*(4), 291–306.

46. Asl, M. N., & Hosseinzadeh, H. (2008). Pharmacological effects of *Glycyrrhiza* sp. *Phytotherapy Research, 22*(6), 709–724. https://doi.org/10.1002/ptr.2362

47. Fiore, C., Eisenhut, M., Ragazzi, E., Zanchin, G., & Armanini, D. (2005). Therapeutic use of liquorice. *Journal of Ethnopharmacology, 99*(3), 317–324. https://doi.org/10.1016/j.jep.2005.04.015

48. Wang, Z. Y., & Nixon, D. W. (2001). Licorice and cancer. *Nutrition and Cancer, 39*(1), 1–11. https://doi.org/10.1207/S15327914nc391_1

49. Nikkhah-Bodaghi, M., Maleki, I., Agah, S., & Hekmatdoost, A. (2019). *Zingiber officinale* and oxidative stress. *Complementary Therapies in Medicine, 43*, 1–6. https://doi.org/10.1016/j.ctim.2019.01.003

50. Brahmbhatt, M., Gundala, S. R., Asif, G., Shamsi, S. A., & Aneja, R. (2013). Ginger phytochemicals and cancer. *Nutrition and Cancer, 65*(2), 263–272. https://doi.org/10.1080/01635581.2013.749925

51. Townsend, E. A., Siviski, M. E., Zhang, Y., Bhatt, D., Bhatt, C., & Emala, C. W. (2013). Ginger and airway smooth muscle relaxation. *American Journal of Respiratory Cell and Molecular Biology, 48*(2), 157–163. https://doi.org/10.1165/rcmb.2012-0231OC

52. Gokhale, A. B., Damre, A. S., Kulkarni, K. R., & Saraf, M. N. (2002). Anti-inflammatory activity of medicinal plants. *Phytomedicine, 9*(5), 433–437. https://doi.org/10.1078/09447110260571578

53. Misra, T., & Bhavsar, G. C. (1986). Antiasthmatic effect of *Achyranthes aspera*. *Indian Journal of Physiology and Pharmacology, 30*(4), 358–362.

54. Dorsch, W., & Ring, J. (1984). Onion extract and allergic reactions. *Allergy, 39*(1), 43–49. https://doi.org/10.1111/j.1398-9995.1984.tb01938.x

55. Slimestad, R., Fossen, T., & Vagen, I. M. (2007). Onions and flavonoids. *Journal of Agricultural and Food Chemistry, 55*(25), 10067–10080. https://doi.org/10.1021/jf0712503

56. Rogerio, A. P., Kanashiro, A., Fontanari, C., da Silva, E. V. G., Lucisano-Valim, Y. M., Soares, E. G., & Faccioli, L. H. (2007). Anti-inflammatory activity of quercetin. *Inflammation Research, 56*(10), 402–408. https://doi.org/10.1007/s00011-007-7077-1

57. Ahmad, A., Husain, A., Mujeeb, M., Khan, S. A., Najmi, A. K., Siddique, N. A., ... Damanhouri, Z. A. (2013). Therapeutic potential of *Nigella sativa*. *Asian Pacific Journal of Tropical Biomedicine, 3*(5), 337–352. https://doi.org/10.1016/S2221-1691(13)60075-1

58. Boskabady, M. H., Mohsenpoor, N., & Takaloo, L. (2010). *Nigella sativa* in asthma. *Phytomedicine, 17*(10), 707–713. https://doi.org/10.1016/j.phymed.2010.01.002

59. Gholamnezhad, Z., Boskabady, M. H., & Hosseini, M. (2015). Immune response of *Nigella sativa*. *Immunopharmacology and Immunotoxicology, 37*(5), 341–349. https://doi.org/10.3109/08923973.2015.1067259

60. Boskabady, M. H., Javan, H., Sajady, M., & Rakhshandeh, H. (2007). Prophylactic effect of *Nigella sativa*. *Fundamental & Clinical Pharmacology, 21*(5), 559–566. https://doi.org/10.1111/j.1472-8206.2007.00509.x

61. Andraws, R., Chawla, P., & Brown, D. L. (2005). Ephedra alkaloids and cardiovascular effects. *Progress in Cardiovascular Diseases, 47*(3), 217–225. https://doi.org/10.1016/j.pcad.2004.08.001

62. Chu, J. H., Li, C. G., & Xue, C. C. (2011). Chinese herbal medicine for asthma. *Evidence-Based Complementary and Alternative Medicine, 2011*, 452346. https://doi.org/10.1093/ecam/nep030

63. Bensky, D., Clavey, S., & Stöger, E. (2004). *Chinese herbal medicine: Materia medica* (3rd ed.). Eastland Press.

64. Sadlon, A. E., & Lamson, D. W. (2010). Eucalyptus oil and antimicrobial effects. *Alternative Medicine Review, 15*(1), 33–47.

65. Worth, H., Schacher, C., & Dethlefsen, U. (2009). Cineole in COPD. *Respiratory Research, 10*(1), 69. https://doi.org/10.1186/1465-9921-10-69

66. Juergens, L. J., Worth, H., & Juergens, U. R. (2020). Cineole therapy perspectives. *Advances in Therapy, 37*(5), 1737–1753. https://doi.org/10.1007/s12325-020-01279-0

67. Juergens, U. R., Dethlefsen, U., Steinkamp, G., Gillissen, A., Repges, R., & Vetter, H. (2003). Cineole in asthma. *Respiratory Medicine, 97*(3), 250–256. https://doi.org/10.1053/rmed.2003.1432

68. Singh, N., & Gilca, M. (2010). *Herbal medicine—Science embraces tradition*. Lambert Academic Publishing.

69. Kumar, S., Singh, B., & Bajpai, V. (2016). *Picrorhiza kurroa* review. *Asian Pacific Journal of Tropical Biomedicine, 6*(3), 258–265. https://doi.org/10.1016/j.apjtb.2015.12.010

70. Dorsch, W., Stuppner, H., Wagner, H., Gropp, M., Demoulin, S., & Ring, J. (1991). Antiasthmatic effects of *Picrorhiza kurroa*. *International Archives of Allergy and Applied Immunology, 95*(2–3), 128–133. https://doi.org/10.1159/000235429

71. Chander, R., Singh, K., Khanna, A. K., Kaul, S. M., Puri, A., Saxena, R., ... Mahdi, A. A. (2003). Antidyslipidemic activity of *Picrorhiza kurroa*. *Indian Journal of Clinical Biochemistry, 18*(2), 8–15. https://doi.org/10.1007/BF02867719

72. Subramoniam, A., Evans, D. A., & Rajasekharan, S. (2001). Immunomodulatory activity of *Picrorhiza kurroa*. *Indian Journal of Pharmacology, 33*(1), 22–30.

73. Hopkins, A. L. (2008). Network pharmacology. *Nature Chemical Biology, 4*(11), 682–690. https://doi.org/10.1038/nchembio.118

74. Fugh-Berman, A., & Ernst, E. (2001). Herb-drug interactions. *British Journal of Clinical Pharmacology, 52*(5), 587–595. https://doi.org/10.1046/j.0306-5251.2001.01469.x

75. European Medicines Agency. (2012). *Guideline on quality of herbal medicinal products/traditional herbal medicinal products*.