



Climate Change and Environmental Stress-Driven Phytochemical Modulation in Medicinal Plants: Implications for Human Health and Disease Management

Muhammad Muzamil^{1*}, Faisal Saeed², Sajjad Hussain³, Muntaha Munir^{4*}, Aisha Nazir^{4*}, Nabeela Nawaz⁴, Sehrish⁴, and Atiq Nasir⁵

¹ Clinical Medicine Department (School of International Education), Hebei North University, 075000, Zhangjiakou, China

² Services Institute of Medical Sciences, Lahore, 54000, Punjab, Pakistan

³ Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China

⁴ Institute of Botany, University of the Punjab, Lahore, 54590, Punjab, Pakistan

⁵ University of Education, Township Campus, Lahore, 54770, Punjab, Pakistan

Article Info

Keywords:

Medicinal plants; Abiotic stress; Phytochemistry; Climate change; Human health; Environmental stress

Date:

Received: 13 November 2025

Revised: 23 January 2026

Accepted: 02 April 2026

Published online: 11 June 2026

Issue date: 15 June 2026

Volume: 7(1), 2026



Copyright: © 2026 by the authors. This article is distributed under the Creative Commons Attribution (CC BY) license, allowing for open access and sharing under specified terms and conditions. (<https://creativecommons.org/licenses/by/4.0/>).

Abstract

Medicinal plants are an essential source of bioactive compounds for traditional and modern healthcare. However, climate change and environmental degradation increasingly influence plant physiology, secondary metabolism, and phytochemical composition, affecting the quality, safety, and therapeutic efficacy of herbal medicines. This review synthesizes current evidence on the effects of climatic factors, including elevated temperature, increased atmospheric CO₂, drought, salinity, altered precipitation, and ultraviolet radiation, together with environmental pollutants such as heavy metals and pesticide residues, on the biosynthesis of pharmacologically important secondary metabolites. Environmental stress modifies carbon allocation, redox homeostasis, oxidative signaling, and metabolic pathways, thereby regulating the accumulation of phenolics, flavonoids, alkaloids, terpenoids, and other specialized metabolites. While moderate stress can enhance the production of valuable phytochemicals, prolonged or severe stress often reduces medicinal quality, destabilizes metabolite profiles, promotes contaminant accumulation, and increases toxicological risks. These phytochemical alterations may influence the effectiveness of plant-derived therapies for cancer, diabetes mellitus, cardiovascular, neurodegenerative, inflammatory, and infectious diseases. The review emphasizes integrating plant stress biology, metabolomics, phytochemistry, pharmacology, toxicology, and quality-control strategies to develop climate-resilient cultivation systems and standardized production frameworks. Such interdisciplinary approaches are essential to ensure the safety, efficacy, sustainability, and global accessibility of medicinal plant-based therapeutics under rapidly changing environmental conditions.

1. Introduction

Medicinal plants represent a cornerstone of global healthcare, underpinning both indigenous healing traditions and contemporary pharmaceutical development. Plant-based remedies have been utilized to ward off and treat a number of maladies for centuries and the present-day drug discovery is

still looking for new therapeutic agents from plants (Nasim et al., 2022). These medicinal properties are mainly attributed to a wide array of secondary metabolites such as alkaloids, flavonoids, terpenoids, phenolic compounds, glycosides, tannins, saponins, and essential oils, which are known for their antioxidant, anti-inflammatory, antimicrobial, antiviral, antidiabetic, cardioprotective, neuroprotective and anticancer

Corresponding Author: *Muntaha Munir

** Aisha Nazir

Email: muntahamunir03@gmail.com

aisha.botany@pu.edu.pk

activities (Asiminicesei et al., 2024). These phytochemicals not only protect plants against biotic and abiotic challenges but also provide significant pharmacological benefits to humans. As result, medicinal plants have gained more relevance in the pharmaceutical, nutraceutical, cosmetic and functional food industry and consistency, quality and chemical composition of bioactive compounds play a significant role in determining therapeutic efficacy and commercial value (Latif & Nawaz, 2025). The therapeutic utility of these plants, however, is not constant but is rather dynamically controlled by environmental factors that affect the synthesis, accumulation, transport and stability of pharmacologically active metabolites during plant growth and development.

The impact of global climate change and increasing environmental degradation is now a significant threat to the productivity, phytochemical quality and therapeutic reliability of medicinal plants (Mykhailenko et al., 2025). Higher temperatures, higher concentration of atmospheric CO₂, more variable precipitation, longer dry spells, soil salinity, stronger ultraviolet radiation, flooding, and the increasing occurrence of extreme climatic events have significant impacts on plant physiological and metabolic processes (Raza et al., 2025). At the same time, medicinal plants face increased stress due to anthropogenic pollution, such as heavy metal contamination, industrial emissions, excessive fertilizer use, pesticide residues, and other environmental pollutants (Jangpangi et al., 2025). Since plants are sessile organisms incapable of escaping adverse environments, they have evolved sophisticated adaptive mechanisms involving morphological, physiological, biochemical, and molecular responses to maintain cellular homeostasis (Ďuranová et al., 2023). Environmental stress activates the production of reactive oxygen species, calcium mediated signaling, abscisic acid, jasmonic acid, salicylic acid and ethylene production, as well as large-scale transcriptional and metabolic reprogramming (Paes de Melo et al., 2022). These interconnected regulatory networks alter carbon allocation, photosynthetic efficiency, nutrient utilization, and enzyme activities, thereby modifying secondary metabolic pathway flux and reshaping phytochemical composition (Liu et al., 2025). These reactions can either increase or decrease the production of medicinally valuable metabolites, depending on the magnitude of the stress factors, the duration of exposure, and their combination in the same plant, leading to significant variability in phytochemicals across different species and growing conditions (Mansinhos et al., 2024).

The plant defense mechanism against oxidative stress often includes the accumulation of antioxidants, such as phenolics, flavonoids, terpenoids, and alkaloids, which are usually increased under moderate stress conditions. These responses

can enhance the pharmacological potential of specific medicinal plants by elevating the levels of bioactive compounds that hold therapeutic significance (Roy et al., 2022). However, chronic or chronic and severe environmental stress may lead to inhibition of plant growth, loss of biomass production, breakdown of metabolic homeostasis, disruption of secondary metabolite biosynthesis, and oxidative injury, thus leading to losses in medicinal properties. In addition, contaminants like cadmium, arsenic, mercury, lead, and lingering pesticide residues can bioaccumulate in medicinal plants and cause significant toxicological risks to consumers (Ashraf et al., 2023). Such stress-induced changes pose significant clinical considerations as changes in phytochemical composition directly affect the biological activity, bioavailability, pharmacokinetics, dosage standardization, efficacy, safety, and potential herb-drug interactions (Laftouhi et al., 2023). Consequently, patients consuming herbal preparations produced under different environmental or geographical conditions may experience inconsistent therapeutic responses, complicating clinical application, quality assurance, regulatory approval, and evidence-based phytotherapy.

Despite increasing recognition of these challenges, a comprehensive synthesis integrating environmental stress biology, phytochemical variability, and human health consequences remains limited. The majority of published studies focus on single environmental stressors, metabolic pathways, or single species of medicinal plants, but not on the interplay of multiple environmental variables, pollutant exposure, metabolic regulation, and therapeutic outcomes. Recent advances in environmental metabolomics, multi-omics technologies, precision herbal medicine, systems biology, and climate-smart cultivation have considerably improved our understanding of stress-mediated phytochemical regulation and provide promising opportunities for safeguarding medicinal plant quality under changing environmental conditions (Shahrajabian et al., 2023; Sokan-Adeaga et al., 2023). However, the implementation of these progressions into standardized production systems and clinical practice demands a more inter-disciplinary integration of the knowledge fields of plant physiology, environmental science, phytochemistry, pharmacology and toxicology, along with clinical medicine. Therefore, this review critically synthesizes current knowledge regarding the effects of climate change and environmental stressors on medicinal plant secondary metabolism, evaluates their consequences for therapeutic efficacy and human health, and highlights future research priorities for developing climate-resilient, standardized, safe, and therapeutically reliable medicinal plant resources.

2. Methodology

2.1 Review Design and Scope

The research was carried out under structured narrative review format where the effects of environment on the phytochemical profile of medicinal plants and their implications to human health and disease management were critically assessed. The review collates the existing evidence on the impact of climate change, abiotic stresses, and environmental pollutants on the biosynthesis, accumulation, and stability of pharmacologically relevant secondary metabolites. Special focus was given on understanding the physiological, biochemical, molecular, and metabolomic mechanisms responsible for stress induced phytochemical changes and the implications for plant quality and therapeutic efficacy and safety. Although a comprehensive and structured literature search strategy was employed, this review was not designed as a formal systematic review or meta-analysis. The available literature covers various medicinal plant species, analyzed environmental stress conditions, experimental techniques and analytical methods, making narrative synthesis the most suitable way to integrate current knowledge, identify emerging research trends and clarify the state of the field.

2.2 Literature Search Strategy

A systematic search of the literature was conducted using four major scientific databases: PubMed, Scopus, Web of Science, and Google Scholar. Peer-reviewed studies published between 2010 and 2026 were included, with particular emphasis on publications from the last five years reflecting recent advances in climate change research, plant stress biology, phytochemistry, environmental metabolomics, and medicinal plant sciences. The final literature search was completed in June 2026. Boolean operators (AND, OR) were used to combine search terms, including medicinal plants, phytochemistry, secondary metabolites, bioactive compounds, environmental stress, climate change, abiotic stress, drought, salinity, elevated CO₂, UV radiation, plant–environment interaction, herbal medicine, environmental metabolomics, and human health. To maximize literature coverage, additional relevant studies were identified through backward and forward citation tracking of key publications.

2.3 Inclusion and Exclusion Criteria

Peer-reviewed original research articles and review papers published in English were considered eligible for inclusion. Priority was given to studies investigating the effects of environmental stressors on medicinal plant physiology, secondary metabolite biosynthesis, phytochemical composition, pharmacological activity, medicinal quality, and implications for human health. Studies employing molecular biology, transcriptomics, metabolomics,

proteomics, and other multi-omics approaches to investigate stress-responsive mechanisms were also included where appropriate. Conference abstracts, editorials, commentaries, book chapters, theses, dissertations, and other non-peer-reviewed publications were excluded. Similarly, research that looked only at plant growth, biomass production or agronomic yield without considering their phytochemical composition, pharmacological activity or clinical relevance was excluded.

2.4 Data Extraction and Evidence Synthesis

The relevant data was collected and categorized based on the type of environmental stressors, medicinal plant species, affected type of phytochemicals, physiological responses, biochemical or molecular mechanisms, signaling pathways, metabolomic changes, pharmacological activities, and therapeutic relevance. Additional information regarding experimental design, stress intensity, duration of exposure, and reported effects on medicinal quality and human health was also recorded where available. A thematic narrative approach was used to synthesize the extracted information. The results were classified into broad themes such as environmental stress factors, regulation of secondary metabolite biosynthesis, phytochemical variability, therapeutic potential, representative medicinal plant case studies, sustainability and future research priorities. This allowed the incorporation of data from a wide range of experimental, biochemical, molecular, metabolomic and clinical studies, the identification of commonalities, mechanisms, trends, and gaps in current knowledge.

3. Environmental Factors Modulating Medicinal Plant Phytochemistry

Environmental conditions are key determinants of medicinal plant growth, physiological functioning, and secondary metabolite biosynthesis. Plants, however, are sessile and cannot escape from sub-optimal environment and thus are required to constantly adapt via suite of tightly regulated physiological, biochemical and molecular processes (Saharan et al., 2022). Climate change and environmental pollution affect not only productivity of plants, but also the bioactive compound concentration, composition and stability, which affect medicinal quality and therapeutic efficacy (Pant et al., 2021). These environmental signals trigger cascades of complex regulatory network pathways involving reactive oxygen species (ROS), calcium signaling, phytohormones, mitogen-activated protein kinase (MAPK) cascades, transcription factors, and epigenetic modifications, which ultimately remodel carbon partitioning and secondary metabolic pathways (Ibragić et al., 2025). Therefore, depending on species-specific adaptations, developmental stage and stress intensity, environmental stress may either induce or suppress the appearance of pharmacologically

relevant metabolites. The intensity of environmental stress is on a hormetic curve with respect to phytochemical accumulation, as conceptually shown in Figure 1.

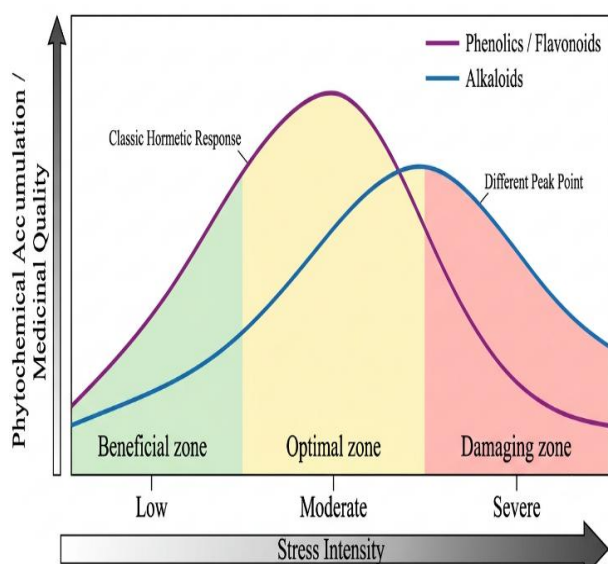


Figure 1. Conceptual stress-phytochemical response (hormetic) curve in medicinal plants

3.1 Climate Change: Temperature, Elevated CO₂, and Altered Precipitation

Climate change is a major driver of alterations in medicinal plant metabolism. As temperature increases, enzyme activity, membrane integrity, respiration rates, and photosynthetic efficiency are impacted, which in turn influences the metabolic allocation towards secondary metabolite production (Qaderi et al., 2023). Moderate temperature increases could trigger the phenylpropanoid pathway, which boosts the levels of phenolics, flavonoids and other antioxidant compounds, contributing to stress tolerance. But extended heat stress causes the disturbance of enzymatic homeostasis, higher protein denaturation, lower metabolite stability, and lower level of key bioactive compounds (Zhang et al., 2025). Increased CO₂ uptake typically increases carbon fixation, and alters carbon partitioning to carbon-rich secondary metabolites, including flavonoids, terpenoids, and phenolic acids. Nonetheless, species-specific differences in nitrogen availability, carbon-use efficiency, and metabolic regulation lead to variable outcomes, with some species showing improved phytochemical accumulation while others experience dilution effects (Alami et al., 2024). Precipitation changes, such as drought, irregular precipitation, and flooding, have a very large impact on plant water status, nutrient uptake, and osmotic balance. However, mild water deficit can increase osmoprotectants and antioxidant compounds, while extended drought or waterlogging can

decrease photosynthesis, biomass production, and overall phytochemical production, impacting the medicinal quality of the crop (Balkrishna et al., 2024).

3.2 Abiotic Stress: Drought, Salinity, and Ultraviolet Radiation

Secondary metabolism is strongly controlled by abiotic stressors like drought, salinity and ultraviolet (UV) radiation, and this regulation occurs through complex signaling mechanisms. Under drought stress, the ABA-mediated signaling pathway and production of reactive oxygen species (ROS) is activated, which triggers the induction of phenylpropanoid enzymes such as phenylalanine ammonia-lyase (PAL), chalcone synthase (CHS), cinnamate-4-hydroxylase (C4H), and 4-coumarate-CoA ligase (4CL) (Ninkuu et al., 2025). During mild to moderate stress conditions, these processes promote the production of flavonoids and phenolics, whereas during extreme drought conditions, metabolic activity decreases and phytochemicals are not produced (Zheng et al., 2023). Salinity stress affects ionic homeostasis and nutrient uptake, which stimulates defense responses and leads to the production of alkaloids, phenolics, and terpenoids, while high salinity affects biosynthetic enzymes causing a loss of metabolites (Ayub et al., 2026). The UV-induced activation of photoreceptor-mediated pathways contributes to increased biosynthesis of flavonoids and phenolic acids, offering greater antioxidant, photoprotective, and anti-inflammatory activities (Abubakar et al., 2023). ROS function as pivotal molecules that connect ABA, jasmonic acid (JA), salicylic acid (SA), ethylene and MAPK in the molecular signaling network. These networks regulate transcription factors like MYB, WRKY, bHLH, and NAC that control genes involved in the biosynthesis of specialized metabolites, including alkaloids, flavonoids, and terpenoids (Rao & Zheng, 2025). Advances in omics technologies have further deepened understanding of these regulatory systems in stress-induced metabolic reprogramming (Imran et al., 2025).

3.3 Soil Conditions, Heavy Metal Contamination, and Agrochemical Pollution

The soil characteristics are important factors that affect the growth, phytochemical content, and safety of medicinal plants. Metabolism and secondary metabolite biosynthesis is controlled by a combination of soil properties such as soil fertility, microbial interactions and physicochemical properties (Eghlima et al., 2025). Heavy metal (Pb, Cd, As, Hg) contaminated soils result in the enrichment of plants in these metals, which induce oxidative stress, impair enzyme activity and interfere with biosynthetic pathways. These contaminants also impact the safety of medicines and their acceptance of herbal medicines by regulators (Zeeshan Ul Haq et al., 2023). Furthermore, the use of agrochemicals like

pesticides, herbicides and overuse of fertilizers further alter metabolism by altering responses to stress and reducing levels of bioactive chemicals. Moreover, nutrient availability may influence precursors supply (especially N and P) and carbon-nitrogen balance that may influence biosynthesis of alkaloids, terpenoids and phenolics (Qaderi et al., 2023). Overall, all these factors interact and affect medicinal quality, therapeutic efficacy and product safety. The interactions

between these environmental factors on phytochemical composition, plant responses and the implications for human health are summarized in Table 1.

4. Environmental Modulation of Phytochemical Composition: Mechanisms and Outcomes

Table 1. Effects of environmental factors on phytochemical composition and medicinal quality of selected medicinal plants

Environmental Factor	Effect on Phytochemicals	Plant Response	Proposed Mechanism	Human Health Impact	Reference
Elevated temperature	Increased phenolics and flavonoids under moderate stress; reduced heat-sensitive metabolites under prolonged stress	Antioxidant capacity varies with stress intensity and species	Reactive oxygen species activate phenylpropanoid biosynthesis and antioxidant defense pathways	Altered efficacy of antioxidant and anti-inflammatory herbal medicines	Zhang et al., 2025
Elevated atmospheric CO ₂	Increased flavonoids, phenolic acids, and terpenoids	Enhanced carbon assimilation promotes secondary metabolism	Greater carbon allocation to phenylpropanoid and terpenoid pathways	Enhanced antioxidant potential but variable phytochemical consistency	Alami et al., 2024
Altered precipitation	Variable phenolics, flavonoids, and antioxidant compounds	Moderate water stress enhances bioactives; prolonged imbalance reduces yield	Water stress induces reactive oxygen species and stress-responsive gene expression	Inconsistent therapeutic efficacy of herbal medicines	Balkrishna et al., 2024
Drought stress	Increased phenolics, flavonoids, and antioxidant compounds under moderate stress	Moderate drought enhances phytochemicals; severe drought suppresses growth	Abscissic acid signaling and reactive oxygen species regulate secondary metabolism	Variable bioactivity and dosage reliability	Zheng et al., 2025
Salinity stress	Increased terpenoids, phenolics, and alkaloids under mild stress; reduced synthesis under severe stress	Adaptive metabolite accumulation up to tolerance threshold	Osmotic stress and ion toxicity activate antioxidant pathways	Altered antimicrobial and anti-inflammatory potential	Zheng et al., 2023
Ultraviolet radiation	Increased flavonoids, anthocyanins, and phenolic acids	Enhanced accumulation of photoprotective compounds	Ultraviolet signaling induces flavonoid biosynthesis	Improved antioxidant and photoprotective properties	Abubakar et al., 2023

The phytochemical composition of medicinal plants is highly dynamic and continuously shaped by environmental conditions throughout development. In contrast to primary metabolites secondary metabolites can be synthesized in response to developmental cues and environmental stimuli to

metabolism is often stimulated by environmental factors like UV exposure, moderate drought, higher temperature, and higher CO₂, which leads to an increase in the accumulation of flavonoids and phenolics (Qaderi et al., 2023). These compounds contribute to antioxidant, anti-inflammatory,

Heavy metal contamination	Disrupted secondary metabolism and accumulation of toxic contaminants	Oxidative stress impairs metabolite synthesis	Metal-induced reactive oxygen species disrupt enzymatic activity	Increased risk of toxicity and carcinogenicity	Zeeshan Ul Haq et al., 2023
Pesticides and industrial pollutants	Reduced bioactive compounds and increased residue accumulation	Lower medicinal quality and phytochemical stability	Pollutants interfere with metabolic enzymes and biosynthetic pathways	Reduced safety and increased chronic health risks	Qaderi et al., 2023
Soil nutrient deficiency	Reduced alkaloids, terpenoids, and other secondary metabolites	Nutrient limitation lowers metabolite production	Restricted precursor availability and altered carbon–nitrogen balance	Reduced pharmacological efficacy	Eghlima et al., 2025
Light intensity	Increased flavonoids, anthocyanins, and carotenoids under high light	Greater antioxidant accumulation under optimal irradiance	Light-regulated transcription factors control secondary metabolism	Enhanced antioxidant and disease-preventive potential	Zhao et al., 2022

which allows cells to adaptively survive and maintain cellular homeostasis (Khan et al., 2025). Therefore, environmental factors can affect the number of metabolites, chemical diversity, biological activity, and molecular stability. These stress-induced changes are regulated by consolidated physiological, biochemical and molecular mechanisms which govern medicinal quality, therapeutic efficacy and safety (Frediansyah et al., 2026).

4.1 Stress-Responsive Secondary Metabolite Classes

The production of secondary metabolites varies with the class of metabolites depending on their biosynthesis and biological function in response to environmental stresses. Under drought, salinity and temperature stress, the accumulation of alkaloids, which are produced via N-dependent pathways, may be part of a plant defense mechanism. Given their pharmacological importance, including analgesic, antimicrobial, anticancer, and neuroactive effects—changes in alkaloid levels have significant therapeutic implications. Severe or prolonged stress, however, can lead to a decrease in alkaloid biosynthesis and disruption of nitrogen metabolism (Laftouhi et al., 2023). Flavonoids and phenolic compounds are highly stress-responsive due to their antioxidant roles in scavenging ROS. Phenylpropanoid

antimicrobial, and cardioprotective effects. Terpenoids, which are synthesized through both the mevalonate (MVA) and methylerythritol phosphate (MEP) pathways, are also significantly affected by light, temperature, carbon availability, and other stress factors, resulting in variations in their volatile and non-volatile components and their range of pharmacological activities (Ali et al., 2025).

4.2 Biochemical and Molecular Regulatory Mechanisms

The biosynthesis of phytochemicals is regulated by environmental stress via complex signaling pathways that translate environmental signals into metabolic adjustments. ROS are important signaling molecules that trigger calcium signaling, MAPK pathways and transcription factors such as MYB, WRKY, bHLH, NAC, and AP2/ERF families. These regulators regulate genes related to shikimate pathway, phenylpropanoid pathway, MVA pathway and MEP pathway, which help direct the production of flavonoids, phenolics, terpenoids, and alkaloids (Patni et al., 2022). Environmental signals are integrated with developmental regulation by phytohormones like ABA, JA, SA, ethylene, and brassinosteroids. Recent breakthroughs in genomics, transcriptomics, proteomics, metabolomics and environmental metabolomics have uncovered intricate

regulatory networks and candidate biomarkers that offer potential for enhancing medicinal plant quality through molecular breeding and climate-smart cultivation practices (Zheng et al., 2025).

4.3 Inter- and Intraspecific Phytochemical Variability

There are substantial differences in phytochemical content between species and even between plants of the same species raised in different environmental conditions. The production of metabolites and their chemical diversity depend greatly on the altitude, soil composition, climate, seasonality, developmental stage, and cultivation practices (Rizvi et al., 2022). This variability leads to differences in pharmacological activity and presents challenges for quality control, authentication, dosage standardization, and reproducibility of therapeutic outcomes (Sarwar et al., 2024).

4.4 Implications for Pharmacological Activity and Therapeutic Efficacy

Pharmacological variability of medicinal plants is directly affected by environmentally induced phytochemical variation. Concentration, compositions, and stabilities of metabolites affect receptor interaction, bioavailability,

4.5 Integrated Molecular Networks Governing Stress-Induced Reprogramming

Phytochemical regulation works as networks of pathways instead of individual pathways. Drought, salinity, temperature, UV radiation, increased CO₂ levels and pollution trigger interconnected signaling pathways involving ROS, calcium signaling, phytohormones, MAPK cascades, and transcription factors (Singh et al., 2026). These signals converge on crucial biosynthetic pathways such as phenylpropanoid, shikimate, MEP, and MVA pathways and regulate enzymes like PAL, CHS, C4H, 4CL, DXS, DXR, GPPS, and HMGR (Alum et al., 2025). Rather than simply increasing or decreasing metabolites, these networks reshape metabolic flux, ultimately determining phytochemical diversity, medicinal quality, and adaptive resilience under environmental change (Chinonso et al., 2025). The integrated molecular signaling network between environmental stressors, secondary metabolism and pharmacology is depicted in Figure 2.

5. Implications for Human Health, Clinical Practice, and Disease Management

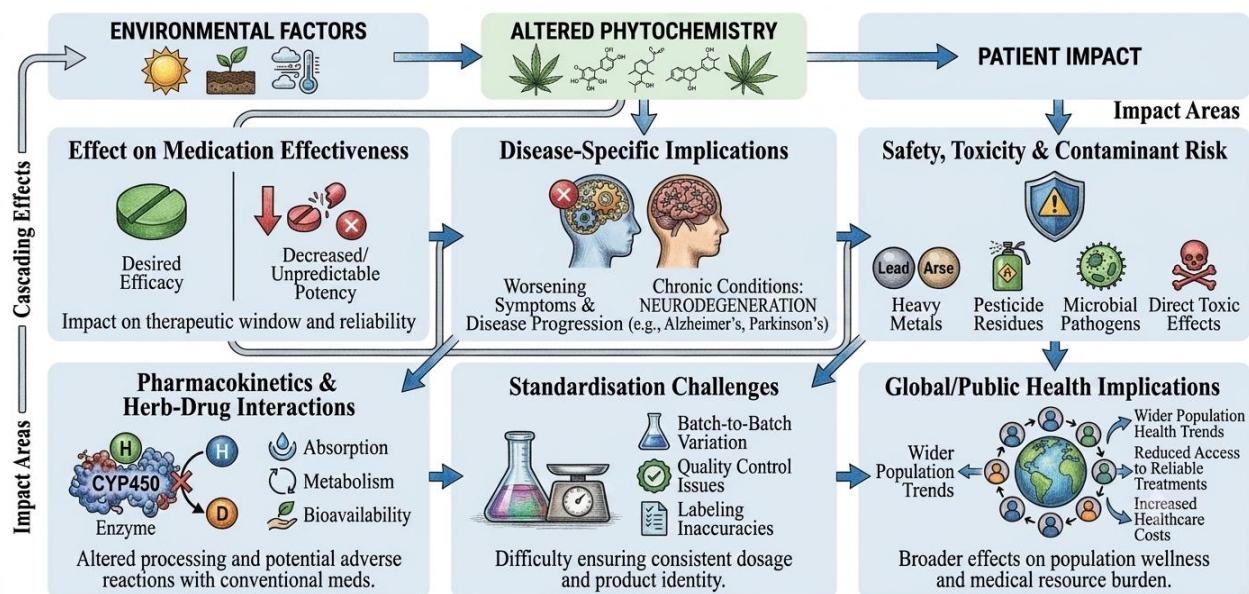


Figure 2. Integrated molecular signaling network linking environmental stress to secondary metabolite biosynthesis and pharmacological activity in medicinal plants

pharmacokinetics, and therapeutic effects. Moderate stress can also make them more antioxidant, antimicrobial, and anticancer, but more stress can lead to more variation in clinical response and less medicinal value. The combined effect of environmental contaminants further enhances the toxicity risk and poses difficulties associated with quality assurance (Rabizadeh et al., 2022, Ullah, 2024).

Environmental regulation of medicinal plant phytochemistry extends far beyond plant physiology, directly influencing the therapeutic efficacy, safety, and clinical reliability of plant-derived medicines. Pharmacological activity, bioavailability and toxicological profile are altered under stress, which changes the concentration, composition and stability of bioactive compounds and therefore the outcome of disease

prevention and treatment (Altanam et al., 2025). Since the use of herbal medicines is becoming more widespread in conventional health care systems, knowledge of the effects of environmental conditions on the quality of medicinal plants is vital for evidence-based clinical practice, regulatory standards, and public health.

5.1 Environmental Modulation of Therapeutic Effectiveness

The therapeutic effectiveness of medicinal plant-derived preparations depends largely on the concentration and balance of pharmacologically active constituents, which are strongly influenced by environmental conditions. Environmental stress often leads to increased production of antioxidants such as flavonoids, phenolics, and other antioxidant metabolites, which can yield greater anti-inflammatory, cardioprotective, and metabolic advantages (Ogwu et al., 2025). On the other hand, high or chronic stress levels can lead to the depletion of important bioactive compounds, which could result in poorer therapeutic effectiveness and variable clinical reactions. Thus, the medicinal properties and the efficiency of herbal medicines made from plants grown in different geographical areas or environmental conditions can show great variation in their therapeutic effect (Bagheri et al., 2024). The detailed clinical and public health impact mechanism of environmental control of medicinal plant phytochemistry is illustrated in Figure 3.

5.2 Disease-Specific Clinical Implications

Environmental modulation of phytochemical composition has important consequences for the management of numerous chronic and infectious diseases. Diabetes mellitus, however, may involve changes in polyphenol, flavonoid and alkaloid levels that can affect glucose metabolism, insulin sensitivity and antioxidant defenses. Similarly, variations in terpenoids, flavonoids, and polyphenols influence antiproliferative, pro-apoptotic, and immunomodulatory activities that contribute to anticancer efficacy (Sun & Shahrajabian, 2023). Changes in the levels of antimicrobial and anti-inflammatory metabolites can also impact therapeutic responses in infectious and inflammatory diseases (Hossain et al., 2025). Emerging evidence also indicates that environmental-induced decrease in levels of neuroprotective compounds such as withanolides from *Withania somnifera* may affect adaptogenic activity and decrease therapeutic potential in anxiety, depression, cognitive decline and neurodegenerative disorders. Overall, the changes in phytochemicals induced by climate change could have a significant impact on the clinical efficacy of plant-based medicines in several disease areas.

5.3 Safety, Toxicity, and Chemical Risk Assessment

The contamination of the environment is a significant obstacle in the safe application of medicinal plants in the clinical field. Environmental contamination can occur in plant tissues without affecting the overall appearance of the

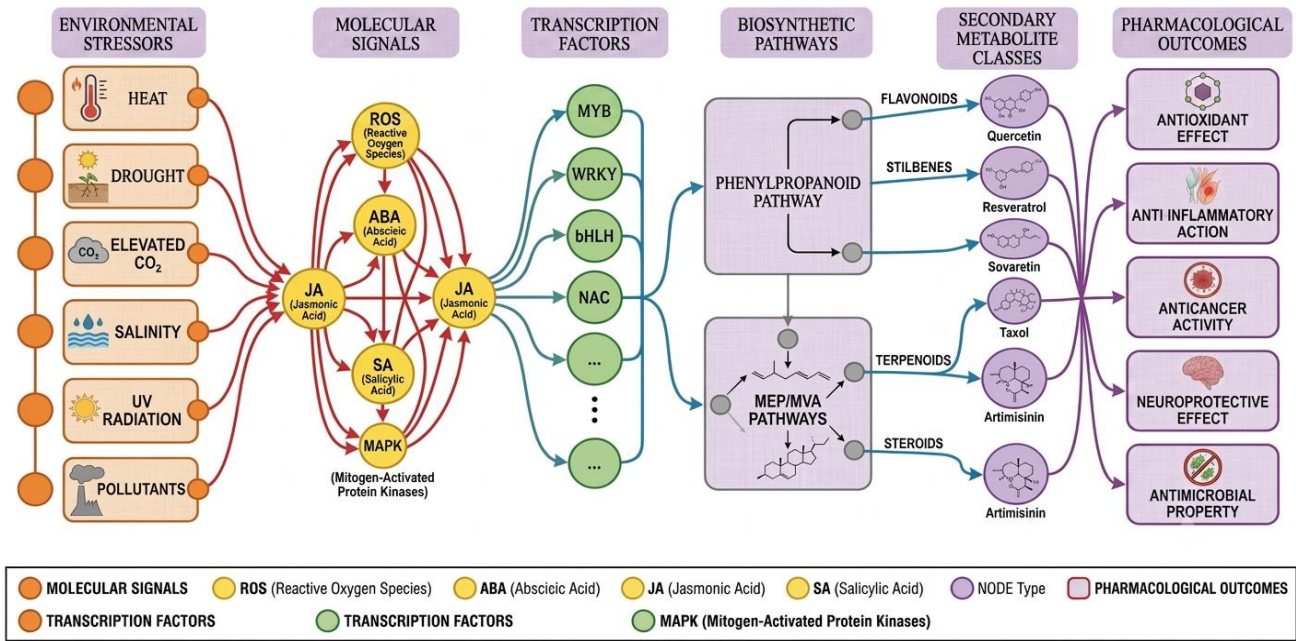


Figure 3. Comprehensive clinical and public health impact framework of environmental regulation of medicinal plant phytochemistry

plants, resulting in unrecognized toxic effects to consumers due to the presence of heavy metal, pesticide residues, industrial pollutants and other contaminants. Chronic exposure to contaminated herbal medicines has been associated with nephrotoxicity, hepatotoxicity, neurotoxicity, reproductive toxicity, and increased cancer risk. Inorganic arsenic in particular has been identified by the International Agency for Research on Cancer (IARC) as a Group 1 human carcinogen, while cadmium has been listed as a probable human carcinogen. Moreover, under high concentrations, stress-induced phytochemicals can have adverse biological effects, which further underscores the need for the strictest quality control, contaminant screening and cultivation traceability prior to clinical application (Vaghela & Gohel, 2023).

5.4 Pharmacokinetics, Bioavailability, and Herb–Drug Interactions

Variability in the environment also affects the abundance of phytochemicals and the pharmacokinetic behavior of medicinal herbs. The absorption, distribution, metabolism, and excretion (ADME) of plant-derived therapeutics (PFTs) is affected by changes in the composition of flavonoids, alkaloids, and terpenoids, which impacts their intestinal absorption, plasma protein binding, metabolic stability, cytochrome P450 (CYP) enzyme activity, and function of drug transporters (Muscolo et al., 2024). These alterations increase the likelihood of clinically relevant herb–drug interactions, particularly among patients receiving anticoagulants, antihypertensive drugs, antidiabetic medications, immunosuppressants, or anticancer therapies (Malik et al., 2025). Herbal products standardized solely by plant weight rather than active phytochemical content are especially susceptible to such pharmacokinetic inconsistencies.

5.5 Challenges for Standardization and Evidence-Based Clinical Practice

Phytochemical standardization is one of the biggest challenges for the integration of herbal medicines into evidence-based medicine. Medicinal plants are complexes of bioactive compounds with varying composition depending on environmental factors, cultivation techniques, harvest time, and postharvest processing, unlike the synthetic pharmaceutical with fixed active ingredients. This variation complicates dose optimization, renders clinical trials non-reproducible and hampers the development of uniform treatment protocols in all countries. Therefore, comprehensive phytochemical profiling, documentation of cultivation history, reporting of environmental metadata and standardized quality assurance should be a part of future clinical research and regulatory frameworks (Sammulia et al., 2025).

5.6 Public Health and Global Healthcare Implications

The biodiversity of medicinal plants is in danger not just due to climate change and environmental degradation, but also the sustainability of herbal healthcare systems. The challenges are important, especially in low- and middle-income countries where medicinal plants are still a major source of healthcare (Alum, 2025). Habitat degradation, degradation of phytochemical quality, contamination, and environmental variability can all negatively impact the accessibility, efficacy and safety of plant-based medicine simultaneously. Sustainable cultivation, climate-tolerant cultivation systems, better regulatory control, international standards and interdisciplinary cooperation among environmental scientists, pharmacologists, clinicians, and toxicologists will be required to address these issues (Bako et al., 2024).

5.7 Regulatory Frameworks for Contaminant Control and Quality Assurance

Effective regulation is needed for the safety and therapeutic uniformity of medicinal products developed from plants. Heavy metal contamination, pesticide residues, mycotoxins, and industrial pollutants require continuous monitoring through validated analytical methods and comprehensive toxicological risk assessment (Butnariu & Bonciu, 2022). A number of international organizations have established guidelines and limits for contaminants in herbal medicines, such as the Codex Alimentarius Commission, the Food and Agriculture Organization (FAO), and the World Health Organization (WHO). Ensuring compliance with these standards, along with implementing good agricultural and collection practices (GACP), good manufacturing practices (GMP), post-market surveillance, and batch-specific phytochemical characterization, is essential to safeguard consumer safety and build trust in herbal therapeutics (Kochanek et al., 2025).

5.8 Future Perspectives: Precision Herbal Medicine

The current advancement of environmental metabolomics, artificial intelligence, multi-omics technologies and pharmacogenomics are making precision herbal medicine a new frontier. Integrating environmental metadata, phytochemical fingerprinting, genomic information, and patient-specific characteristics may enable the development of standardized, personalized, and environmentally informed therapeutic strategies. These can lead to increased accuracy of doses, reduced herb–drug interactions, better clinical reproducibility, and sustained safety and efficacy of medicinal plant interventions in the rapidly changing environment (Popovic & Rijkers, 2025).

6. Case Studies: Environmental Influences on Representative Medicinal Plants

Representative medicinal plant species provide compelling evidence that environmental conditions directly influence phytochemical biosynthesis, medicinal quality, and therapeutic performance. The production of bioactive compounds is controlled by common physiological and molecular mechanisms, such as oxidative stress signaling, hormonal regulation and metabolic reprogramming, although the individual species respond differently to environmental stress (Ibragić et al., 2025). A summary of the effects of environmental stress on phytochemical composition and therapeutic relevance across representative medicinal plants is presented in Table 2. The case studies presented below show the influence of climatic variables, soil properties and environmental pollutants on the pharmacologic value and clinical acceptability of common medicinal plants.

6.1 *Curcuma longa* (Turmeric)

The medicinal activity of *Curcuma longa* is largely attributed to curcuminoids, particularly curcumin, which possess potent antioxidant, anti-inflammatory, antimicrobial, and anticancer properties (Jain et al., 2025). Curcuminoid biosynthesis is strongly influenced by soil fertility, temperature, water availability, and cultivation practices. Moderate environmental stress may stimulate curcuminoid accumulation through enhanced antioxidant defense, whereas prolonged heat stress, nutrient deficiency, and poor soil conditions reduce curcumin biosynthesis and overall rhizome quality. Furthermore, cultivation in heavy metal-contaminated soils may result in cadmium, lead, and arsenic accumulation within rhizomes, compromising both therapeutic efficacy and consumer safety (Wang et al., 2026).

6.2 *Azadirachta indica* (Neem)

The pharmacological properties of *Azadirachta indica* are primarily associated with limonoids such as azadirachtin and nimbin, together with diverse flavonoids and phenolic compounds (Afzal et al., 2026). They are also dependent on water availability, temperature, soil fertility, and precipitation when they are synthesized. Mild drought conditions can stimulate the synthesis of defense secondary metabolites, further increasing the antimicrobial and anti-inflammatory properties. But excessive environmental stress and soil pollution from pesticides or heavy metals can affect the phytochemical balance, diminish medicinal benefits, and lead to toxic residue in neem-based products (Wylie & Merrell, 2022; Ibrahim et al., 2023).

6.3 *Withania somnifera* (Ashwagandha)

Withania somnifera is valued for its withanolides, a class of steroidal lactones responsible for adaptogenic, immunomodulatory, anti-inflammatory, and neuroprotective activities (Jain et al., 2024). Their accumulation is highly responsive to environmental factors, including soil nutrient

availability, temperature, irrigation regime, and drought intensity. Mild environmental stress frequently enhances withanolide biosynthesis by activating stress-responsive metabolic pathways, whereas severe or prolonged stress suppresses growth, decreases phytochemical production, and reduces therapeutic potential (Khabiya et al., 2024). These environmentally induced variations are particularly relevant for neurological disorders, stress-related diseases, and immune dysfunction, where consistent withanolide concentrations are essential for predictable clinical outcomes (Kumar et al., 2023).

6.4 *Allium sativum* (Garlic)

The therapeutic efficacy of *Allium sativum* depends largely on allicin and related organosulfur compounds, which contribute to its antimicrobial, cardioprotective, antioxidant, and antihypertensive activities (Ammarellou et al., 2022). Their biosynthesis is closely linked to the sulphur content of the soil, nutrient balance, irrigation and environmental conditions. The concentration of allicin can significantly fluctuate depending on the growing conditions, potentially impacting the medicinal properties and therapeutic benefits. Moreover, heavy metals and agrochemical residues can be introduced into tissues of garlic during cultivation due to contaminated soils, which raise concerns about long-term safety and quality assurance of medicinal preparations (Tudu et al., 2022).

6.5 *Camellia sinensis* (Green Tea)

The health-promoting properties of *Camellia sinensis* are primarily attributed to catechins, particularly epigallocatechin gallate (EGCG), which exhibit strong antioxidants, anti-inflammatory, cardioprotective, and anticancer activities. The biosynthesis of catechins is strongly influenced by environmental factors such as altitude, solar radiation, ultraviolet exposure, temperature, and soil composition (Zhao et al., 2022). Higher elevations tend to have more polyphenols in the tea plant because there are more ultraviolet exposure and moderate environmental stress. The climate change effects, however, could impact the location of suitable cultivation areas and the catechin profile, which could impact the nutritional value, therapeutic effects and the commercial quality of green tea products globally (Brimson et al., 2022).

6.6 Integrative Insights from Representative Medicinal Plants

Despite species-specific responses, these representative medicinal plants demonstrate a common principle: environmental conditions profoundly influence phytochemical composition, medicinal quality, and therapeutic reliability through coordinated metabolic reprogramming. Although the accumulation of potentially

useful compounds under moderate stress conditions may increase medicinal benefits, the use of such stress may have a negative effect on the concentration of useful compounds

- Provide routine monitoring of heavy metals, pesticide residues and other environmental contaminants prior to clinical use.

Table 2. Overview of representative medicinal plants, major environmental stressors, stress-induced phytochemical changes, and their implications for medicinal quality and therapeutic efficacy

Medicinal Plant	Key Phytochemicals	Major Environmental Stressors	Moderate Stress Effect	Severe Stress Effect	Therapeutic Applications	Safety Concerns
<i>Curcuma longa</i> (Turmeric)	Curcuminoids	Temperature, soil fertility, water	Increased curcuminoid production	Reduced curcumin; heavy metal accumulation	Anti-inflammatory, antioxidant, anticancer	Heavy metal contamination
<i>Azadirachta indica</i> (Neem)	Azadirachtin, flavonoids	Temperature, rainfall, soil fertility	Increased bioactive metabolites	Altered phytochemistry; contaminant residues	Antimicrobial, anti-inflammatory	Pesticide and heavy metal residues
<i>Withania somnifera</i> (Ashwagandha)	Withanolides	Drought, nutrients, temperature	Enhanced withanolid synthesis	Reduced growth and withanolides	Adaptogenic, neuroprotective, immunomodulatory	Variable phytochemical content
<i>Allium sativum</i> (Garlic)	Allicin, organosulfur compounds	Sulfur nutrition, irrigation	Enhanced allicin synthesis	Reduced allicin; heavy metal accumulation	Antimicrobial, cardioprotective, antihypertensive	Heavy metals and agrochemical residues
<i>Camellia sinensis</i> (Green Tea)	Catechins (EGCG)	UV, altitude, temperature	Enhanced catechin accumulation	Altered catechin profile and reduced quality	Antioxidant, cardioprotective, anticancer	Climate-related quality decline

during long or intense stress conditions, and risk accumulation of contaminants (Asiminicesei et al., 2024). The above observations highlight the important role of cultivation and environmental management in providing medicinal plant efficacy other than genetic background.

Collectively, these case studies highlight several priorities for research and clinical practice:

- Document cultivation history, geographical origin, and agroclimatic conditions during medicinal plant sourcing.
- Use quantitative phytochemical profiling, and not only the identification of herbs or plant biomass to standardize herbal products.

- Combine environmental monitoring, metabolomic profiling and pharmacological evaluation for improved quality control, reproducibility and therapeutic consistency of products derived from medicinal plants.

7. Sustainability, Conservation, and Climate-Resilient Medicinal Plant Management

The long-term therapeutic value of medicinal plants depends not only on their phytochemical composition but also on the sustainability of the ecosystems in which they occur. Plant resources are vulnerable to climate change, habitat loss, biodiversity loss, and anthropogenic pressure, both in terms of availability and medicinal value, as well as genetic diversity (Mykhailenko et al., 2025). To ensure the

sustainability of plant-based healthcare, it is essential to implement comprehensive conservation measures encompassing sustainable cultivation, biodiversity protection, quality control, and climate resilient management. These approaches will help to protect medicinal plant resources with their pharmacological values, ecological stability, and socio-economic values.

7.1 Biodiversity Loss and Overexploitation of Wild Medicinal Plant Populations

The global pharmaceutical, nutraceutical and traditional medicine markets are increasing the demand for medicinal plants, leading to unsustainable harvesting of wild populations. Over-exploitation leads to depletion of population size, genetic diversity, and reproductive potential, which makes many species more susceptible to environmental changes and local extinction (Shukla, 2023). Loss of genetic diversity also reduces the number of valuable alleles for stress tolerance, disease resistance and biosynthesis of secondary metabolites available for future breeding programmes or pharmaceutical discovery programmes. Additionally, degradation of natural habitats impacts ecological interactions between pollinators, soil microorganisms, and associated vegetation that are crucial for sustaining healthy populations of medicinal plants (Zaman et al., 2025).

7.2 Climate Change Impacts on Medicinal Plant Distribution and Chemical Ecology

Climate change is reshaping the geographical distribution, phenology, ecological interactions, and phytochemical composition of medicinal plant species (Takubessi et al., 2025). Increased temperatures, changed rain patterns, longer droughts, and more extreme weather events are moving suitable habitat to higher altitudes and latitudes while decreasing productivity in the traditional cultivation areas. Simultaneously, environmental stress modifies secondary metabolite biosynthesis, resulting in altered chemical ecology and variable medicinal quality. Species possessing narrow ecological ranges or specialized habitat requirements are particularly vulnerable to climate-driven distributional shifts, creating challenges for conservation planning, sustainable harvesting, and the long-term consistency of herbal medicines (Raj & Jhariya, 2023).

7.3 Sustainable Cultivation and Good Agricultural and Collection Practices (GACP)

Sustainable cultivation is a valuable approach to limit the pressure on wild medicinal plant populations and increase phytochemical uniformity and product safety. The implementation of Good Agricultural and Collection Practices (GACP), as recommended by the World Health Organization and the Food and Agriculture Organization,

provides standardized guidance for site selection, soil and water management, sustainable harvesting, contamination prevention, post-harvest handling, traceability, and documentation. Additionally, implementing complementary methods like organic farming, precision irrigation, integrated nutrient management, controlled environment agriculture, and precision agriculture technologies can further enhance phytochemical quality, minimize environmental impact, and adaptability to climate variability (Mbelebele et al., 2024). The integrated framework for climate-resilient, sustainable medicinal plant management ensuring therapeutic quality and safety is depicted in Figure 4.

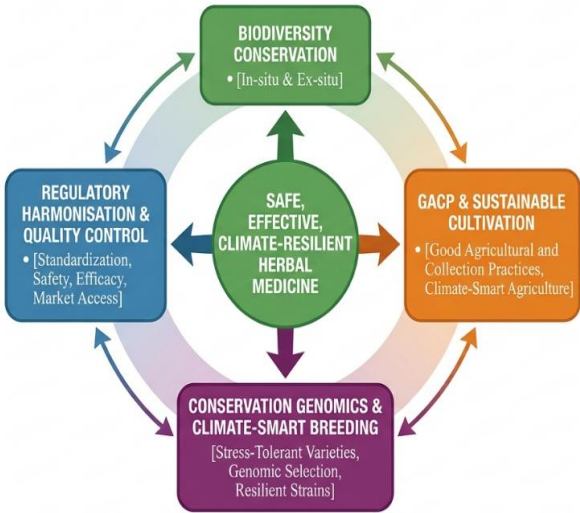


Figure 4. Integrated framework for climate-resilient, sustainable medicinal plant management ensuring therapeutic quality and safety

7.4 Conservation Genomics and Climate-Smart Breeding for Phytochemical Resilience

With recent advances in conservation genomics, new opportunities have emerged for improving disease resistance and medicinal value of plant resources. Genomic analysis can be used for identification of genes and molecular markers associated with stress tolerance and biosynthesis of secondary metabolites and climate adaptation, which can be utilized in marker assisted selection and climate smart breeding programs (Kardbhajne & Dhadse, 2026). Combination of genomic data, transcriptomic, metabolomic and phenotypic data allows predicting phytochemical responses under climate scenarios and breeding medicinal plant varieties which are able to retain their therapeutic activity under climate stress. Such strategies will play an increasingly important role in securing medicinal plant resources under rapidly changing climatic conditions (Dissanayaka & Rathnayaka, 2025).

7.5 Quality Control, Standardization, and Regulatory Oversight

To ensure the quality, safety and therapeutic uniformity of the medicinal plants, extensive quality control systems are to be followed which go beyond botanical authentication. Modern quality assurance should integrate phytochemical fingerprinting, contaminant analysis, environmental monitoring, batch-to-batch metabolite quantification, and complete traceability of cultivation conditions throughout the production chain. To ensure product reliability, expand international trade, boost scientific reproducibility, and speed clinical acceptance of evidence-based herbal medicines, harmonized regulatory frameworks based on internationally accepted standards are needed. The need for better coordination between regulatory agencies is thus evident to overcome the inconsistencies that exist across national regulatory systems (Maity, 2023).

7.6 Public Health, Health Equity, and Policy Integration

Preserving medicinal plant resources is closely related to health equity around the world. Medicinal plants continue to be the main source of healthcare for significant parts of the population in many LMICs. As a result, vulnerable groups with access to conventional medicines are adversely affected by environmental degradation, biodiversity loss, and a decline in the quality of phytochemicals. Therefore, national governments and international organisations should integrate medicinal plant conservation into public health policies, national and international biodiversity policies, essential medicines policies and sustainable development policies. Integrating environmental conservation with healthcare planning will strengthen resilience of both ecosystems and healthcare systems under future climate change scenarios (dos Santos et al., 2023; Alum, 2024).

7.7 Interdisciplinary Integration: Linking Ecology, Phytochemistry, and Health Systems

The future sustainability of medicinal plant-based healthcare depends on interdisciplinary collaboration among plant scientists, ecologists, phytochemists, pharmacologists, clinicians, toxicologists, conservation biologists, and policymakers. Traditional ecological knowledge, environmental metabolomics, artificial intelligence, remote sensing, and precision agriculture will be integrated with traditional ecological knowledge, boosting conservation planning, cultivation and quality assurance. International collaborative research networks and long-term monitoring programmes are required to produce multi-environment datasets that will allow prediction of the effects of climate change on phytochemical diversity and medicinal quality and therapeutic efficacy. Such integrated approaches will be fundamental for developing climate-resilient medicinal plant

production systems that ensure sustainable, safe, and effective plant-derived medicines for future generations.

8. Research Gaps, Challenges, and Future Directions

Despite considerable advances in understanding how environmental factors regulate medicinal plant phytochemistry, major scientific, technological, and regulatory challenges continue to limit the development of standardized, climate-resilient herbal medicines. The current state of knowledge is still scattered among plant physiology, phytochemistry, pharmacology, toxicology, and clinical sciences, and it is still not possible to predict the effects of environmental variation on the therapeutic activity and safety of plant drugs. Addressing these limitations requires coordinated interdisciplinary research integrating environmental monitoring, molecular biology, metabolomics, artificial intelligence, and clinical validation.

8.1 Environmental-Integrated Standardization of Medicinal Plants

At present, quality control is mostly based on the botanical authentication and quantification of a limited number of marker compounds without taking into account the effects of cultivation environment, climatic variability, soil characteristics and agricultural practice. Future standardization frameworks should integrate environmental metadata, metabolomic fingerprints, genomic information, and real-time quality monitoring throughout the production chain to ensure reproducible phytochemical composition and therapeutic consistency (Olorunsogo et al., 2024).

8.2 Standardized Cultivation and Climate-Smart Production Systems

Considerable variation in medicinal plant quality arises from differences in irrigation, fertilization, soil management, harvesting time, drying conditions, and storage practices. While Good Agricultural and Collection Practices (GACP) gives good guidance, it is not consistently adopted regionally. Further studies are needed to establish cultivation protocols for each species, with the assistance of controlled-environment agriculture and precision farming technologies, and climate-smart production systems to ensure phytochemical stability in response to evolving environmental conditions.

8.3 Strengthening Clinical Translation

Environmental conditions of cultivation of medicinal plants are not mentioned in most of the pharmacological studies. This means that variations in phytochemical content often make interpretation of biological activity difficult and studies are not easily reproducible. Future experimental and clinical investigations should incorporate standardized botanical authentication, batch-specific phytochemical

characterization, environmental metadata, contaminant screening, and harmonized extraction protocols. To develop solid evidence for medicinal plant-based therapeutics, large-scale, multi-center clinical trials are required, and only trials of such size will provide the necessary chemical characterization of plant material, which is crucial for these trials (Morris et al., 2022).

8.4 Advanced Analytical Technologies and Multi-Omics Integration

Recent advances in metabolomics, transcriptomics, proteomics, genomics, and environmental metabolomics have significantly improved understanding of stress-responsive secondary metabolism. Regardless, the translation of large-scale molecular data into clinically relevant biomarkers is not straightforward due to the lack of standardized analysis and a poverty of reference databases. The integration of multi-omics data, identification of predictive biomarkers, modelling of responses of phytochemicals under future climate scenarios and improving medicinal plant improvement are potential areas where AI, machine learning and systems biology can play a role (Singh et al., 2024).

8.5 Environmental Safety, Regulatory Harmonization, and Global Policy

Environmental contaminant monitoring remains inconsistent throughout global medicinal plant supply chains. Heavy metals, pesticide residues, mycotoxins, and industrial pollutants require internationally harmonized analytical standards and comprehensive risk assessment frameworks that incorporate cumulative exposure, bioaccumulation, and contaminant–phytochemical interactions (Parven et al., 2025). There is also a need for enhanced cooperation among international regulatory organizations to harmonize quality control, phytochemical characterization, labelling, contamination levels and post-market surveillance of herbal medicines.

8.6 Conservation and Climate Adaptation

Moving forward, conservation strategies need to incorporate biodiversity protection, community-based resource management, sustainable harvesting, conservation genomics, and climate modelling to help conserve medicinal plant diversity in the face of rapid climate change. Incorporation of predictive ecological models, which associate the environmental variables with phytochemical composition and species distribution, will support the identification of the climate sensitive medicinal plants and inform conservation priorities (Shetty et al., 2023).

8.7 Future Research Priorities

Future studies should focus on:

- Developing protocols that are harmonized and understood internationally for cultivation, harvest, and postharvest.
- Linkage of the environmental metadata with metabolomic, genomic and clinical databases.
- AI-assisted prediction of phytochemical variation under changing climate scenarios.
- Multicenter clinical trials using standardized and chemically authenticated medicinal plants.
- Development of international phytochemical standards and quality-control materials.
- Harmonization of regulatory frameworks governing medicinal plant safety, efficacy, and quality.
- The integrated environmental monitoring and toxicological evaluation for comprehensive contaminant risk assessment.
- Establishment of interdisciplinary international research consortia linking plant sciences, environmental sciences, pharmacology, toxicology, and clinical medicine.

9. Conclusion

Despite their importance as sources of bioactive compounds in traditional and modern medicine, medicinal plants are still essential to healthcare, whose therapeutic properties are very much dependent on the environment. This review demonstrates that climate change, abiotic stress, soil quality, and environmental pollution collectively regulate secondary metabolite biosynthesis through interconnected molecular networks involving reactive oxygen species, phytohormones, transcription factors, and metabolic pathway reprogramming. The phytochemical alterations that occur under environmental conditions directly affect the medicinal quality, pharmacological action, pharmacokinetic behavior, safety, and reliability of the medicinal product. Therapeutically important phytochemicals can be stimulated by moderate environmental stress, providing opportunities for controlled stress elicitation to enhance medicinal quality. On the other hand, chronic and intense environmental stressors, combined with heavy metal pollution and agrochemical pollution, result in a disruption of the phytochemical integrity, a decrease in therapeutic consistency, and an increase in toxicological risks. Consequently, ensuring the safety and effectiveness of herbal medicines requires integrating environmental monitoring, phytochemical characterization, contaminant assessment, and standardized cultivation throughout the medicinal plant production chain. However, further advances require integration of approaches from various disciplines including plant stress biology, environmental sciences, metabolomics,

phytochemistry, pharmacology, toxicology, genomics, artificial intelligence and clinical medicine. Some approaches such as climate-smart cultivation systems, conservation genomics, precision herbal medicine, AI-assisted multi-omics analysis, and internationally harmonized regulation are promising in protecting medicinal plant resources and guaranteeing the reproducible therapeutic performance. In the context of increasing environmental shifts, the combination of environmental sustainability and evidence-based phytomedicine will be key to ensuring long-term safety, efficacy, and worldwide availability of medicinal plant-based therapeutics.

10. Funding

No funding was received for this study.

11. Acknowledgment

The authors acknowledge Dr. Muhammad Shafiq, Assistant Professor, Institute of Botany, University of the Punjab, Lahore, Pakistan, for his valuable guidance and constructive feedback.

12. Conflict of Interest

The authors declare no conflict of interest.

13. Authors' Contribution

Muntaha Munir and Aisha Nazir contributed to conceptualization and supervision. Muhammad Muzamil, Sajjad Haider, and Faisal Saeed were involved in methodology development, data collection, analysis, and writing the original draft. Nabeela Nawaz, Sehrish, and Atiqah Nasir contributed to review and editing of the manuscript.

14. SDGs Addressed

This study aligns with the United Nations Sustainable Development Goals (SDGs), particularly SDG 3 (Good Health and Well-being) by supporting the safe and effective use of medicinal plants for disease prevention and management; SDG 13 (Climate Action) by addressing the impacts of climate change and environmental stress on medicinal plant phytochemistry; and SDG 15 (Life on Land) by highlighting the conservation and sustainable utilization of plant biodiversity under changing environmental conditions.

References

- Abubakar, A., Yusuf, H., Syukri, M., Nasution, R., Yusuf, M., & Idroes, R. (2023). Heavy metals contamination in geothermal medicinal plant extract (*Chromolaena odorata* Linn). *Global Journal of Environmental Science and Management*, 9(4), 995–1004.
<https://doi.org/10.22035/gjesm.2023.04.22>
- Afzal, S., Shoaib, S., Jahan, R., Shadab, M., Alomary, M. N., & Ansari, M. A. (2026). Medicinal and nutritional importance of *Azadirachta indica* in human health. In *Medicinal plants and their bioactive compounds in human health: Volume 2* (pp. 1–15). Springer Nature Singapore. https://doi.org/10.1007/978-981-95-3620-7_11
- Alami, M. M., Guo, S., Mei, Z., Yang, G., & Wang, X. (2024). Environmental factors on secondary metabolism in medicinal plants: Exploring accelerating factors. *Medicinal Plant Biology*, 3, e016. <https://doi.org/10.48130/mpb-0024-0016>
- Ali, I., Zahid, T., & Rehman, H. M. A. (2025). Exploring climate-induced alterations in medicinal plant phytochemistry: Implications for sustainable pharmaceutical development. *Pakistan Journal of Medical & Cardiological Review*, 4(3), 708–717.
- Altanam, S. Y., Darwish, N., & Bakillah, A. (2025). Exploring the interplay of antioxidants, inflammation, and oxidative stress: Mechanisms, therapeutic potential, and clinical implications. *Diseases*, 13(9), 309. <https://doi.org/10.3390/diseases13090309>
- Alum, E. U. (2024). Climate change and its impact on the bioactive compound profile of medicinal plants: Implications for global health. *Plant Signaling & Behavior*, 19(1). <https://doi.org/10.1080/15592324.2024.2419683>
- Alum, E. U. (2025). Sustainable harvesting of medicinal plants: Balancing therapeutic benefits with environmental conservation. *Agroecology and Sustainable Food Systems*, 49(3), 380–385. <https://doi.org/10.1080/21683565.2024.2421948>
- Alum, E. U., Udechukwu, C. D., & Obasi, D. C. (2025). RNA signaling in medicinal plants: An overlooked mechanism for phytochemical regulation. *Biochemistry and Biophysics Reports*, 42, 102032. <https://doi.org/10.1016/j.bbrep.2025.102032>
- Ammarellou, A., Yousefi, A. R., Heydari, M., Uberti, D., & Mastinu, A. (2022). Biochemical and botanical aspects of *Allium sativum* L. sowing. *BioTech*, 11(2), 16. <https://doi.org/10.3390/biotech11020016>
- Ashraf, M. V., Pant, S., Khan, M. A. H., Shah, A. A., Siddiqui, S., Jeridi, M., Alhamdi, H. W. S., & Ahmad, S. (2023). Phytochemicals as antimicrobials: Prospecting Himalayan medicinal

- plants as source of alternate medicine to combat antimicrobial resistance. *Pharmaceuticals*, 16(6), 881. <https://doi.org/10.3390/ph16060881>
- Asiminicesei, D.-M., Fertu, D. I., & Gavrilescu, M. (2024). Impact of heavy metal pollution in the environment on the metabolic profile of medicinal plants and their therapeutic potential. *Plants*, 13(6), 913. <https://doi.org/10.3390/plants13060913>
- Ayub, A., Khan, Z., Elboughdiri, N., Malik, S. M., Ayub, M., Kriaa, K., Maatki, C., Hadrich, B., Singh, R., & Wani, A. K. (2026). Transcriptional regulation and functional dynamics of secondary metabolites in plant adaptation and defense. *Journal of Plant Growth Regulation*, 45, 1–27. <https://doi.org/10.1007/s00344-026-12193-0>
- Bagheri, E., Shori, A. B., Baba, A. S., & Alzahrani, A. J. (2024). Phytochemical analysis and medicinal properties of some selected traditional medicinal plants. *International Journal of Agriculture & Biosciences*, 13(4), 687. <https://doi.org/10.47278/journal.ijab/2024.177>
- Bako, B., Danladi, A. H., Bulus, G. G., & Shinggu, J. P. (2024). A comprehensive review of solvent-induced variability in antioxidant profiling of plant extracts: *Justicia secunda*. *Progress in Chemical and Biochemical Research*, 7(1), 1–21. <https://doi.org/10.48309/pcbr.2024.417487.1292>
- Balkrishna, A., Yadav, P., Yadav, P., Saini, A., Kumar, B., Singh, N., Sharma, D., & Arya, V. P. (2024). Factors affecting biodiversity and conservation of medicinal plants. In *Ethnopharmacology and OMICS Advances in Medicinal Plants Volume 1: Uncovering Diversity and Ethnopharmacological Aspects* (pp. 1–16). Springer Nature Singapore. https://doi.org/10.1007/978-981-97-2367-6_1
- Brimson, J. M., Prasanth, M. I., Kumaree, K. K., Thitilertdech, P., Malar, D. S., Tencomnao, T., & Prasansuklab, A. (2022). Tea plant (*Camellia sinensis*): A current update on use in diabetes, obesity, and cardiovascular disease. *Nutrients*, 15(1), 37. <https://doi.org/10.3390/nu15010037>
- Butnariu, M., & Bonciu, E. (2022). Assessment of some hazards associated with dangerous chemicals. In R. A. Bhat, M. A. Dervash, K. R. Hakeem, & K. Z. Masoodi (Eds.), *Environmental biotechnology* (pp. 1–37). Apple Academic Press. <https://doi.org/10.1201/9781003277279-1>
- Chinonso, A. D., Kayode, A. A., Adondua, M. A., & Chinekwu, U. K. (2025). Biochemistry of traditional herbal compounds and their molecular targets. *Pharmacognosy Reviews*, 19(37). <https://doi.org/10.5530/phrev.20252302>
- Dissanayaka, D. D., & Rathnayaka, R. M. (2025). Biological approaches in the sustainability of medicinal plant production: Improving resilience and reducing environmental footprint. In *Biological Innovations for Environmental Sustainability* (p. 197)
- dos Santos, M. L., Chandran, D., Lejaniya, A. S., & da Silva, L. E. (2023). Conservation and sustainable use of medicinal plants. In S. Jha & M. Halder (Eds.), *Medicinal plants: Biodiversity, biotechnology and conservation* (Sustainable Development and Biodiversity, Vol. 33). Springer, Singapore. https://doi.org/10.1007/978-981-19-9936-9_13
- Đúranová, H., Šimora, V., Ďurišová, L., Olexiková, L., Kovár, M., & Požgajová, M. (2023). Modifications in ultrastructural characteristics and redox status of plants under environmental stress: A review. *Plants*, 12(8), 1666. <https://doi.org/10.3390/plants12081666>
- Eghlima, G., Tafreshi, Y. M., Aghamir, F., Ahadi, H., & Hatami, M. (2025). Regional environmental impacts on growth traits and phytochemical profiles of *Glycyrrhiza glabra* L. for enhanced medicinal and industrial use. *BMC Plant Biology*, 25(1), 116. <https://doi.org/10.1186/s12870-025-06147-z>
- Frediansyah, A., Nurkolis, F., Taslim, N. A., Ali, M. F., Millotti, G., Buršić, M., Putranto, R. A., Kim, B., Tjandrawinata, R. R., & Santini, A. (2026). Climate-driven metabolic reprogramming in medicinal plants: Implications for phytochemical composition, therapeutic efficacy, and safety. *Revista Brasileira de Farmacognosia*, 36(1), 45. <https://doi.org/10.1007/s43450-026-00762-z>
- Hossain, M. S., Wazed, M. A., Asha, S., Amin, M. R., & Shimul, I. M. (2025). Dietary phytochemicals in health and disease: Mechanisms, clinical evidence, and applications—A comprehensive review. *Food Science & Nutrition*, 13, e70101. <https://doi.org/10.1002/fsn3.70101>
- Ibragić, S., Dahija, S., & Karalija, E. (2025). The good, the bad, and the epigenetic: Stress-induced metabolite regulation and transgenerational effects. *Epigenomes*, 9(2), 10. <https://doi.org/10.3390/epigenomes9020010>
- Ibrahim, S., Kwakuri, S. S., & Arif, M. (2023). *Azadirachta indica* (neem): An important medicinal plant: A literature review of its chemistry, biological

- activities, role in COVID-19 management and economic importance. *Journal of Pharmacognosy and Phytochemistry*, 12(6), 59–65. <https://doi.org/10.22271/phyto.2023.v12.i6a.14769>
- Imran, M., Wu, Q., Guanming, C., & Zhou, L. (2025). Multifaceted roles and regulatory mechanisms of MYB transcription factors in plant development, secondary metabolism, and stress adaptation: Current insights and future prospects. *GM Crops & Food*, 16(1), 626–655. <https://doi.org/10.1080/21645698.2025.2559489>
- Jain, D., Singh, K., Gupta, P., Gupta, J. K., Sahu, P. K., Dwivedi, S., Sharma, M. C., & Kumar, S. (2025). Exploring synergistic benefits and clinical efficacy of turmeric in management of inflammatory and chronic diseases: A traditional Chinese medicine based review. *Pharmacological Research – Modern Chinese Medicine*, 14, 100572. <https://doi.org/10.1016/j.prmcm.2025.100572>
- Jain, V., Chaturvedi, S., Jamil, S., Tyagi, R., Arya, S., & Madan, S. (2024). Ashwagandha: Botanic occurrence, conventional uses, and significance in heart, metabolic, renal and hepatic disorder. *Nutrition & Food Science*, 54(8), 1337–1355. <https://doi.org/10.1108/NFS-01-2024-0030>
- Jangpangi, D., Patni, B., Chandola, V., & Chandra, S. (2025). Medicinal plants in a changing climate: Understanding the links between environmental stress and secondary metabolite synthesis. *Frontiers in Plant Science*, 16, 1587337. <https://doi.org/10.3389/fpls.2025.1587337>
- Kardbhajne, A., & Dhadse, S. (2026). Climate change and medicinal plant conservation: Challenges and strategies. *Journal of Indian Association for Environmental Management*, 46(1), 12–21. <https://doi.org/10.47915/jiaem.v46i1.21508>
- Khabiya, R., Choudhary, G. P., Jnanasha, A. C., Kumar, A., & Lal, R. K. (2024). An insight into the potential varieties of Ashwagandha (Indian ginseng) for better therapeutic efficacy. *Ecological Frontiers*, 44(3), 444–450. <https://doi.org/10.1016/j.chnaes.2023.06.009>
- Khan, A., Kanwal, F., Ullah, S., Fahad, M., Tariq, L., Altaf, M. T., Riaz, A., & Zhang, G. (2025). Plant secondary metabolites—central regulators against abiotic and biotic stresses. *Metabolites*, 15(4), 276. <https://doi.org/10.3390/metabo15040276>
- Kochanek, A., Graż, K., Potok, H., Gronba-Chyła, A., Kwaśny, J., Wiewiórska, I., Ciula, J., Basta, E., & Łapiński, J. (2025). Micro- and nanoplastics in the environment: Current state of research, sources of origin, health risks, and regulations—A comprehensive review. *Toxics*, 13(7), 564. <https://doi.org/10.3390/toxics13070564>
- Kumar, A., Husain, D., Lal, R. K., Singh, S., Singh, V., & Gupta, A. K. (2023). Genetic diversity and future prospects in *Withania somnifera* (L.) Dunal: An assessment based on quantitative traits in different accessions of Ashwagandha. *The Nucleus*, 66(2), 151–159. <https://doi.org/10.1007/s13237-023-00423-9>
- Laftouhi, A., Eloutassi, N., Ech-Chihbi, E., Rais, Z., Abdellaoui, A., Taleb, A., Beniken, M., Nafidi, H.-A., Salamatullah, A. M., Bourhia, M., & Taleb, M. (2023). The impact of environmental stress on the secondary metabolites and the chemical compositions of the essential oils from some medicinal plants used as food supplements. *Sustainability*, 15(10), 7842. <https://doi.org/10.3390/su15107842>
- Latif, R., & Nawaz, T. (2026). Medicinal plants and human health: A comprehensive review of bioactive compounds, therapeutic effects, and applications. *Phytochemistry Reviews*, 25, 2299–2342. <https://doi.org/10.1007/s11101-025-10194-7>
- Liu, S., An, X., Xu, C., He, D., Li, X., Chen, C., Guo, B., Xu, D., & Huang, J. (2025). Integrative transcriptomic-physiological analysis deciphers nitrogen-mediated carbon reallocation balancing growth and flavonoid metabolism in *Epimedium pubescens*. *Frontiers in Plant Science*, 16, 1539445. <https://doi.org/10.3389/fpls.2025.1539445>
- Maity, S. (2023). Sustainable healthcare: Medicinal plants and environmental balance in Ayurveda. In S. Roychoudhury, T. Sanyal, K. Sen, & S. M. Sanyal (Eds.), *A basic overview of environment and sustainable development* (Vol. 2, pp. 166–184). International Academic Publishing House. <https://doi.org/10.52756/boesd.2023.e02.011>
- Malik, I. M., Bhat, A. H., Majeed, D., & Nabi, N. (2025). Environmental factors influencing phytochemical production for enhanced phytochemical defense. In *Phytochemical Arsenal: Understanding Plant Defense Mechanisms Against Nematodes* (pp. 118–150). Bentham Science Publishers. <https://doi.org/10.2174/97898153226751250101>
- Mansinhos, I., Gonçalves, S., & Romano, A. (2024). How climate change-related abiotic factors affect the

- production of industrial valuable compounds in Lamiaceae plant species: A review. *Frontiers in Plant Science*, 15, 1370810. <https://doi.org/10.3389/fpls.2024.1370810>
- Mbelebele, Z., Mdoda, L., Ntlanga, S. S., Nontu, Y., & Gidi, L. S. (2024). Harmonizing traditional knowledge with environmental preservation: Sustainable strategies for the conservation of indigenous medicinal plants (IMPs) and their implications for economic well-being. *Sustainability*, 16(14), 5841. <https://doi.org/10.3390/su16145841>
- Morris, C. E., Géniaux, G., Nédellec, C., Sauvion, N., & Soubeyrand, S. (2022). One Health concepts and challenges for surveillance, forecasting, and mitigation of plant disease beyond the traditional scope of crop production. *Plant Pathology*, 71, 86–97. <https://doi.org/10.1111/ppa.13446>
- Muscolo, A., Mariateresa, O., Giulio, T., & Mariateresa, R. (2024). Oxidative stress: The role of antioxidant phytochemicals in the prevention and treatment of diseases. *International Journal of Molecular Sciences*, 25(6), 3264. <https://doi.org/10.3390/ijms25063264>
- Mykhailenko, O., Jalil, B., McGaw, L. J., Echeverría, J., Takubessi, M., & Heinrich, M. (2025). Climate change and the sustainable use of medicinal plants: A call for “new” research strategies. *Frontiers in Pharmacology*, 15, 1496792. <https://doi.org/10.3389/fphar.2024.1496792>
- Mykhailenko, O., Jalil, B., McGaw, L. J., Echeverría, J., Takubessi, M., & Heinrich, M. (2025). Climate change and the sustainable use of medicinal plants: A call for “new” research strategies. *Frontiers in Pharmacology*, 15, 1496792. <https://doi.org/10.3389/fphar.2024.1496792>
- Nasim, N., Sandeep, I. S., & Mohanty, S. (2022). Plant-derived natural products for drug discovery: Current approaches and prospects. *Nucleus*, 65(3), 399–411. <https://doi.org/10.1007/s13237-022-00405-3>
- Ninkuu, V., Aluko, O. O., Yan, J., Zeng, H., Liu, G., Zhao, J., Li, H., Chen, S., & Dakora, F. D. (2025). Phenylpropanoids metabolism: Recent insight into stress tolerance and plant development cues. *Frontiers in Plant Science*, 16, 1571825. <https://doi.org/10.3389/fpls.2025.1571825>
- Ogwu, M. C., Izah, S. C., & Joshua, M. T. (2025). Ecological and environmental determinants of phytochemical variability in forest trees. *Phytochemistry Reviews*, 24, 5109–5137. <https://doi.org/10.1007/s11101-025-10066-0>
- Olorunsogo, T. O., Ogugua, J. O., Muonde, M., Maduka, C. P., & Omotayo, O. (2024). Environmental factors in public health: A review of global challenges and solutions. *World Journal of Advanced Research and Reviews*, 21(1), 1453–1466. <https://doi.org/10.30574/wjarr.2024.21.1.0176>
- Paes de Melo, B., Carpinetti, P. d. A., Fraga, O. T., Rodrigues-Silva, P. L., Fioresi, V. S., de Camargos, L. F., & Ferreira, M. F. d. S. (2022). Abiotic stresses in plants and their markers: A practice view of plant stress responses and programmed cell death mechanisms. *Plants*, 11(9), 1100. <https://doi.org/10.3390/plants11091100>
- Pant, P., Pandey, S., & Dall’Acqua, S. (2021). The influence of environmental conditions on secondary metabolites in medicinal plants: A literature review. *Chemistry & Biodiversity*, 18(11), e2100345. <https://doi.org/10.1002/cbdv.202100345>
- Parven, A., Meftaul, I. M., Venkateswarlu, K., & Megharaj, M. (2025). Herbicides in modern sustainable agriculture: Environmental fate, ecological implications, and human health concerns. *International Journal of Environmental Science and Technology*, 22(2), 1181–1202. <https://doi.org/10.1007/s13762-024-05818-y>
- Patni, B., Bhattacharyya, M., Kumari, A., & Purohit, V. K. (2022). Alarming influence of climate change and compromising quality of medicinal plants. *Plant Physiology Reports*, 27(1), 1–10. <https://doi.org/10.1007/s40502-021-00616-x>
- Popovic, L., & Rijkers, G. T. (2026). Phytochemicals: Principles and practice. *Biology*, 15(1), 18. <https://doi.org/10.3390/biology15010018>
- Qaderi, M. M., Martel, A. B., & Strugnell, C. A. (2023). Environmental factors regulate plant secondary metabolites. *Plants*, 12(3), 447. <https://doi.org/10.3390/plants12030447>
- Rabizadeh, F., Mirian, M. S., Doosti, R., Kiani-Anbouhi, R., & Eftekhari, E. (2022). Phytochemical classification of medicinal plants used in the treatment of kidney disease based on traditional Persian medicine. *Evidence-Based Complementary and Alternative Medicine*, 2022, 8022599. <https://doi.org/10.1155/2022/8022599>
- Raj, A., & Jhariya, M. K. (2023). Conservation and sustainable uses of medicinal plants

- phytochemicals. In S. C. Izah, M. C. Ogwu, & M. Akram (Eds.), *Herbal medicine phytochemistry* (Reference Series in Phytochemistry). Springer, Cham. https://doi.org/10.1007/978-3-031-21973-3_39-1
- Rao, M. J., & Zheng, B. (2025). The role of polyphenols in abiotic stress tolerance and their antioxidant properties to scavenge reactive oxygen species and free radicals. *Antioxidants*, 14(1), 74. <https://doi.org/10.3390/antiox14010074>
- Raza, A., Khare, T., Zhang, X., Rahman, M. M., Hussain, M., Gill, S. S., Chen, Z.-H., Zhou, M., Hu, Z., & Varshney, R. K. (2025). Novel strategies for designing climate-smart crops to ensure sustainable agriculture and future food security. *Journal of Sustainable Agriculture and Environment*, 4, e70048. <https://doi.org/10.1002/sac2.70048>
- Rizvi, A., Ahmed, B., Khan, M. S., El-Beltagi, H. S., Umar, S., & Lee, J. (2022). Bioprospecting plant growth promoting rhizobacteria for enhancing the biological properties and phytochemical composition of medicinally important crops. *Molecules*, 27(4), 1407. <https://doi.org/10.3390/molecules27041407>
- Roy, A., Khan, A., Ahmad, I., Alghamdi, S., Rajab, B. S., Babalghith, A. O., Alshahrani, M. Y., Islam, S., & Islam, M. R. (2022). Flavonoids: A bioactive compound from medicinal plants and its therapeutic applications. *BioMed Research International*, 2022, 5445291. <https://doi.org/10.1155/2022/5445291>
- Saharan, B. S., Brar, B., Duhan, J. S., Kumar, R., Marwaha, S., Rajput, V. D., & Minkina, T. (2022). Molecular and physiological mechanisms to mitigate abiotic stress conditions in plants. *Life*, 12(10), 1634. <https://doi.org/10.3390/life12101634>
- Sammulia, S. F., Suhaera, S., Prayoga, D. K., Pitriani, P., Ramadhania, Z. M., Fristiody, A., & Milanda, T. (2026). Fermentation-induced changes in phytochemical composition and pharmacological activities of Zingiberaceae plants: Insight from *in vitro* and *in vivo* studies. *Drug Design, Development and Therapy*, 20, 604038. <https://doi.org/10.2147/DDDT.S604038>
- Sarwar, M., Saleem, M. F., Ullah, N., Maqsood, H., & Ahmad, H. (2024). Physiological ecology of medicinal plants: implications for phytochemical constituents. In *Herbal medicine phytochemistry: Applications and trends* (pp. 1679–1711). Springer International Publishing. https://doi.org/10.1007/978-3-031-43199-9_35
- Shahrajabian, M. H., Kuang, Y., Cui, H., Fu, L., & Sun, W. (2023). Metabolic changes of active components of important medicinal plants on the basis of traditional Chinese medicine under different environmental stresses. *Current Organic Chemistry*, 27, 1–25. <https://doi.org/10.2174/1385272827666230807150910>
- Shetty, S. S., Deepthi, D., Harshitha, S., Sonkusare, S., Naik, P. B., & Madhyastha, H. (2023). Environmental pollutants and their effects on human health. *Heliyon*, 9(9), e19496. <https://doi.org/10.1016/j.heliyon.2023.e19496>
- Shukla, S. K. (2023). Conservation of medicinal plants: Challenges and opportunities. *Journal of Medicinal Botany*, 7, 5–10. <https://doi.org/10.25081/jmb.2023.v7.8437>
- Singh, D. D., Yadav, D. K., & Shin, D. (2026). Phytochemicals and redox modulation: Molecular mechanisms, clinical relevance, and therapeutic perspectives. *Antioxidants*, 15(2), 272. <https://doi.org/10.3390/antiox15020272>
- Singh, P. K., Kumar, U., Kumar, I., Dwivedi, A., Singh, P., Mishra, S., Seth, C. S., & Sharma, R. K. (2024). Critical review on toxic contaminants in surface water ecosystem: Sources, monitoring, and its impact on human health. *Environmental Science and Pollution Research*, 31(45), 56428–56462. <https://doi.org/10.1007/s11356-024-34932-0>
- Sokan-Adeaga, A. A., Sokan-Adeaga, M. A., Sokan-Adeaga, E. D., Oparaji, A. N., Edris, H., Tella, E. O., ... Amubieya, O. E. (2023). Environmental toxicants and health adversities: A review on interventions of phytochemicals. *Journal of Public Health Research*, 12(2), 22799036231181226. <https://doi.org/10.1177/22799036231181226>
- Sun, W., & Shahrajabian, M. H. (2023). Therapeutic potential of phenolic compounds in medicinal plants—natural health products for human health. *Molecules*, 28(4), 1845. <https://doi.org/10.3390/molecules28041845>
- Takubessi, M. I., Jalil, B., & Heinrich, M. (2025). The impact of climate change on medicinal plants and natural products: A scoping review. *Frontiers in Pharmacology*, 16, 1697581. <https://doi.org/10.3389/fphar.2025.1697581>

- Tudu, C. K., Dutta, T., Ghorai, M., Biswas, P., Samanta, D., Oleksak, P., Jha, N. K., Kumar, M., Radha, Proćkó, J., Pérez de la Lastra, J. M., & Dey, A. (2022). Traditional uses, phytochemistry, pharmacology and toxicology of garlic (*Allium sativum*), a storehouse of diverse phytochemicals: A review of research from the last decade focusing on health and nutritional implications. *Frontiers in Nutrition*, 9, 929554. <https://doi.org/10.3389/fnut.2022.929554>
- Tufail, T., Fatima, S., Ain, H. B. U., Ikram, A., Noreen, S., Rebezov, M., AL-Farga, A., Saleh, R., & Shariati, M. A. (2025). Role of phytonutrients in the prevention and treatment of chronic diseases: A concrete review. *ACS Omega*, 10(13), 12724–12755. <https://doi.org/10.1021/acsomega.4c02927>
- Ullah, S. (2024). The effects of plant age on phytochemical and geographical distribution of *Euphorbia helioscopia* (sun spurge or madwoman's milk) (Euphorbiaceae) from Arang District, Bajaur. *Pakistan Journal of Weed Science Research*, 29(4), 206–212. <https://doi.org/10.17582/journal.PJWSR/2023/29.4.206.212>
- Vaghela, N., & Gohel, S. (2023). Medicinal plant-associated rhizobacteria enhance the production of pharmaceutically important bioactive compounds under abiotic stress conditions. *Journal of Basic Microbiology*, 63, 308–325. <https://doi.org/10.1002/jobm.202200361>
- Wang, Z., Zhong, W., Zhao, W., Zhou, Q., Wang, Y., Zhang, B., & Lin, Z. (2026). Turmeric: A comprehensive review of its botany, traditional uses, phytochemistry, and mechanisms as a functional food. *Nutrients*, 18(8), 1197. <https://doi.org/10.3390/nu18081197>
- Wylie, M. R., & Merrell, D. S. (2022). The antimicrobial potential of the neem tree *Azadirachta indica*. *Frontiers in Pharmacology*, 13, 891535. <https://doi.org/10.3389/fphar.2022.891535>
- Zaman, W., Ayaz, A., & Park, S. (2025). Climate change and medicinal plant biodiversity: Conservation strategies for sustainable use and genetic resource preservation. *Genetic Resources and Crop Evolution*, 72, 6275–6308. <https://doi.org/10.1007/s10722-025-02410-2>
- Zeeshan Ul Haq, M., Yu, J., Yao, G., Yang, H., Iqbal, H. A., Tahir, H., Cui, H., Liu, Y., & Wu, Y. (2023). A systematic review on the continuous cropping obstacles and control strategies in medicinal plants. *International Journal of Molecular Sciences*, 24(15), 12470. <https://doi.org/10.3390/ijms241512470>
- Zhang, C., Zhong, X., Bao, S., Urtnasan, M., & Li, M. (2025). Main factors affecting the efficacy of medicinal plants during the cultivation process. *Frontiers in Plant Science*, 16, 1634926. <https://doi.org/10.3389/fpls.2025.1634926>
- Zhao, T., Li, C., Wang, S., & Song, X. (2022). Green tea (*Camellia sinensis*): A review of its phytochemistry, pharmacology, and toxicology. *Molecules*, 27(12), 3909. <https://doi.org/10.3390/molecules27123909>
- Zheng, C., Yang, Q., Wang, X., Chen, Y., He, R., Li, X., Pan, H., Zhuo, R., Qu, T., & Qiu, W. (2025). Transcription factors involved in plant stress and growth and development: NAC. *Agronomy*, 15(4), 949. <https://doi.org/10.3390/agronomy15040949>
- Zheng, H., Fu, X., Shao, J., Tang, Y., Yu, M., Li, L., Huang, L., & Tang, K. (2023). Transcriptional regulatory network of high-value active ingredients in medicinal plants. *Trends in Plant Science*, 28(4), 429–446. <https://doi.org/10.1016/j.tplants.2022.12.007>
- Zheng, Z., Gao, J., Ma, Y., & Hou, X. (2025). Cellular and molecular mechanisms of phytochemicals against inflammation-associated diseases and viral infection. *Cell Biology International*, 49, 606–633. <https://doi.org/10.1002/cbin.70011>

Disclaimer/Publisher's Note: The views, opinions, and data presented in all publications are exclusively those of the respective author(s) and contributor(s) and do not reflect the stance of Pagepal or its editorial team. Pagepal and the editor(s) disclaim any responsibility for harm to individuals or damage to property resulting from the use of any ideas, techniques, instructions, or products mentioned in the content.