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Review Article

Phytochemical chaos: Impacts of climate change and pollution on medicinal plant chemistry, bioactivity and toxicity

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Abstract

Environmental stressors, including climate change, pollution, and urbanization, significantly impact the phytochemical composition, medicinal efficacy, and economic viability of plant-derived therapeutics. Rising global temperatures, drought stress, and CO_2 fluctuations influence secondary metabolite synthesis, leading to variability in bioactive compound concentrations. Pollution-driven contamination, including heavy metal bioaccumulation and pesticide residues, poses serious safety concerns for herbal medicines, while habitat destruction and genetic erosion due to urbanization threaten medicinal plant biodiversity. However, emerging technologies like CRISPR, AI-driven phytochemical profiling, and precision agriculture provide promising solutions to mitigate these challenges. Sustainable agricultural practices, stringent pollution control measures, and regulatory frameworks integrating real-time environmental monitoring are crucial to preserving medicinal plant resources. The integration of green extraction technologies, blockchain-based traceability systems, and interdisciplinary collaborations can enhance phytochemical stability, optimize production, and ensure the quality of plant-based therapeutics. A proactive, technology-driven approach is essential to securing the future of herbal medicine and maintaining ecological integrity while addressing global healthcare needs.

Keywords: Bioactive compounds, Blockchain traceability, Climate change, CRISPR, Heavy metal contamination, Herbal medicine standardization, Medicinal plants, Phytochemical composition.

Introduction

Medicinal plants have long served as critical sources of therapeutic agents, forming the basis of traditional healing systems and contributing significantly to modern pharmacopoeia. Their efficacy is largely attributed to secondary metabolites such as alkaloids, flavonoids, terpenoids, and phenolics, which possess diverse pharmacological properties. However, rapidly accelerating environmental changes driven by climate variability, anthropogenic pollution, and urban expansion are profoundly altering the phytochemical landscape of these medicinal species (Patwardhan & Mashelkar, 2020). These stressors impact plant biochemistry by modulating biosynthetic pathways, leading to shifts in metabolite profiles that can either enhance or diminish therapeutic potential, bioavailability, and safety (Ahmed *et al*., 2022). Climate change is a dominant modifier of plant metabolism. Rising temperatures, fluctuating precipitation patterns, and elevated atmospheric CO_2 have been shown to influence the synthesis of bioactive compounds (Choudhary *et al*., 2021). For example, increased heat stress has been linked to changes in flavonoid production in *Camellia sinensis*, affecting antioxidant potency (Lin *et al*., 2020). Drought stress alters nutrient uptake, influencing terpene and alkaloid biosynthesis, while CO_2 enrichment modulates phenolic and glycoside levels in several species (Kumar & Bhatnagar, 2019). Concurrently, pollution—via airborne particulates, heavy metals, and microplastics—induces oxidative stress and disrupts enzymatic functions, leading to the accumulation of toxic metabolites or suppression of pharmacologically active compounds (Singh *et al*., 2023).

Urbanization further compounds these effects through habitat degradation, genetic erosion, and anthropogenic selection pressures that shift the metabolic balance of phytochemical pathways (Meena *et al*., 2022). Together,

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these multifactorial stressors raise serious concerns about the future consistency, safety, and economic viability of herbal medicines.

This review aims to systematically evaluate how climate change, pollution, and urbanization collectively influence medicinal plant chemistry, therapeutic efficacy, and toxicity. It highlights key biochemical pathways affected by environmental stressors, explores emerging adaptive mechanisms, and proposes frameworks for sustainable plant-based drug development in a rapidly changing world.

Although several recent reviews have examined environmental impacts on phytochemistry, most focus on single-factor influences, such as elevated CO_2 or temperature (Gupta & Sharma, 2021). These reductionist models fail to account for the real-world complexity of multiple, co-occurring environmental stressors that interact to influence plant metabolism. Moreover, few studies have systematically synthesized how such phytochemical shifts translate into changes in pharmacological bioactivity, pharmacokinetics, and consumer safety (Desai *et al*., 2023). To address these critical gaps, this review offers a novel, integrated approach by examining the compounded effects of simultaneous stressors—such as heat, drought, and pollutant exposure—on secondary metabolite dynamics in medicinal plants. Importantly, this review emphasizes underrepresented ethnomedicinal species from fragile ecosystems, which are often neglected in mainstream phytochemical databases (Nikam *et al*., 2022). It also incorporates cutting-edge methodological developments, including AI-assisted phytochemical modeling (Verma & Khan, 2023), multi-omics integration (e.g., transcriptomics and ecological metabolomics) for stress-response mapping (Khalid *et al*., 2021), and predictive ecological frameworks for phytochemical stability. Additionally, real-world implications are discussed, such as the rising cost and complexity of phytochemical extraction, shifting efficacy profiles, and the toxicological risks posed by environmental contaminant accumulation (Rao *et al*., 2024). By bridging phytochemistry, environmental science, and pharmacoeconomics, this review provides a forward-looking framework for sustainable medicinal plant use, supporting conservation efforts and guiding adaptive strategies for herbal drug development amid a planetary health crisis.

Study selection criteria

This study follows a systematic approach to identify relevant literature on the impact of climate change, pollution, and urbanization on medicinal plant phytochemistry. Studies were selected based on relevance, methodological rigor, and inclusion of quantitative data on phytochemical composition changes.

Data sources and search strategy

A comprehensive literature search was conducted using databases such as PubMed, Scopus, Web of Science, and Google Scholar. Keywords included "climate change and medicinal plants," "pollution impact on phytochemicals," "urbanization and plant bioactivity," and "toxicity of medicinal plants under environmental stress" (Zhao *et al*., 2021). Boolean operators (AND, OR) were used to refine the search.

Inclusion and exclusion criteria

Inclusion criteria

- Peer-reviewed studies published in the last 15 years (Desai *et al*., 2023).
- Research examining phytochemical changes in medicinal plants due to environmental stressors (Ahmed *et al*., 2022).

Studies providing quantitative data on phytochemical profiles, bioactivity, or toxicity

Exclusion criteria

- Non-peer-reviewed articles, conference abstracts, and opinion pieces.
- Studies lacking phytochemical analysis or environmental context.
- Duplicates or redundant publications (Kumar & Bhatnagar, 2019).

Climate change influences phytochemical composition by altering plant secondary metabolism through environmental stressors such as temperature, drought, elevated CO_2, UV-B radiation, and flooding. These stresses modulate key biosynthetic pathways (e.g., shikimate and phenylpropanoid), leading to quantitative and qualitative shifts in metabolites such as flavonoids, alkaloids, phenolics, and essential oils. Such changes act as adaptive responses for plant survival but also directly impact the therapeutic efficacy and safety of medicinal plants.

Impact of climate change on phytochemical composition

Climate change exerts a profound and multifaceted influence on the phytochemical composition of medicinal and food plants by disrupting ecological stability through variations in temperature, atmospheric CO_2 concentration, and water availability (Bhatia & Goyal, 2021). These environmental perturbations regulate the metabolic flux within plants, thereby altering the biosynthesis, accumulation, and spatial distribution of both primary and secondary metabolites. Such biochemical shifts not only affect the therapeutic efficacy, nutritional quality, and aroma profiles of these plants but also compromise their ecological fitness and resilience (Sharma *et al*., 2020).

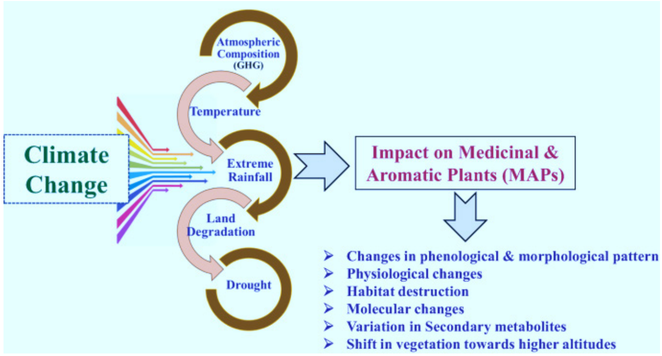

Figure 1: Schematic representation of the impact of climate change on medicinal and aromatic plants (MAPs)

As illustrated in Figure 1, climate change initiates a cascade of environmental consequences—ranging from increased greenhouse gas emissions and temperature rise to extreme precipitation patterns, land degradation, and drought. These abiotic stressors collectively drive morphological, phenological, physiological, and molecular changes in medicinal and aromatic plants (MAPs), resulting in habitat fragmentation, reduced population viability, and altered metabolite profiles. Particularly, the synthesis of key secondary metabolites—such as alkaloids, phenolics, terpenoids, and flavonoids—is either enhanced or suppressed depending on the type and intensity of climatic stress.

Table 1 presents a comprehensive matrix of plant-specific responses to climate-driven stressors, underscoring the dynamic nature of phytochemical expression. For instance, elevated temperature has been shown to upregulate flavonoid and anthocyanin pathways in *Camellia sinensis* (Tea) and *Vitis vinifera* (Grape), while concurrently downregulating alkaloid and terpenoid biosynthesis in *Coffea arabica* (Coffee) and *Capsicum annuum* (Chili Pepper) (Lin *et al.*, 2020). Drought conditions, by contrast, stimulate the accumulation of adaptive secondary metabolites such as phenolics and terpenoids in stress-resilient species like *Ocimum sanctum* (Holy Basil) and *Hypericum perforatum* (St. John's Wort), thereby enhancing their pharmacological properties (Choudhary *et al.*, 2021). Furthermore, elevated CO_2 levels have been linked to increased production of bioactive compounds—particularly phenolics and terpenoids—in species such as *Panax ginseng* (Ginseng) and *Mentha* spp. (Mint), while salinity and UV-B stress modulate osmoprotectant and flavonoid pathways, respectively, enhancing stress tolerance and bioactivity (Kumar & Bhatnagar, 2019).

Taken together, these observations emphasize the need for an integrated and adaptive phytochemical monitoring strategy to safeguard the medicinal value of plants under changing climatic scenarios. Such insights are instrumental for developing climate-smart cultivation practices and guiding conservation priorities for vulnerable MAP species

Temperature and phytochemical variability

Temperature fluctuations significantly impact enzymatic activities involved in phytochemical biosynthesis. Elevated temperatures accelerate metabolic pathways

Table 1: Comprehensive impact of climate change factors on phytochemical composition

Climate change factors	*Effect on phytochemicals*	*Example plants*
Increased temperature	Modulates phenolic content; enhances flavonoids and anthocyanins, reduces alkaloids and terpenoids	*Camellia sinensis* (Tea), *Vitis vinifera* (Grape), *Solanum lycopersicum* (Tomato)
Extreme heat stress	Reduces alkaloids, disrupts metabolic pathways, lowers antioxidant activity	*Coffea arabica* (Coffee), *Capsicum annuum* (Chili Pepper)
Cooler temperatures	Increases anthocyanins, enhances antioxidant properties	*Fragaria × ananassa* (Strawberry), *Vaccinium myrtillus* (Bilberry)
Drought stress	Enhances accumulation of phenolics, terpenoids, and alkaloids as adaptive responses to stress	*Ocimum sanctum* (Holy Basil), *Hypericum perforatum* (St. John's Wort), *Rosmarinus officinalis* (Rosemary)
Waterlogging	Reduces secondary metabolite accumulation, disrupts phenylpropanoid pathway	*Glycine max* (Soybean), *Oryza sativa* (Rice)
Elevated CO_2	Increases production of phenolics and terpenoids; reduces nitrogen-based alkaloids	*Panax ginseng* (Ginseng), *Mentha sp.* (Mint), *Gynostemma pentaphyllum* (Jiaogulan)
Combined CO_2 & drought	Synergistic effect; boosts carbon-based metabolites, flavonoids, and antioxidants	*Artemisia annua* (Sweet Wormwood), *Salvia officinalis* (Sage)
Salinity stress	Alters secondary metabolite synthesis; enhances osmoprotectants like proline and betaines	*Atriplex halimus* (Saltbush), *Salicornia europaea* (Glasswort)
UV radiation increase	Stimulates flavonoid biosynthesis, enhances photoprotective pigments	*Lavandula angustifolia* (Lavender), *Thymus vulgaris* (Thyme)

such as the shikimate pathway, leading to increased synthesis of phenolic compounds and flavonoids (Sharma *et al*., 2020). For example, phenylalanine ammonia-lyase (PAL), a key enzyme in the phenylpropanoid pathway, is upregulated under heat stress, promoting the production of flavonoids and anthocyanins (Choudhary *et al*., 2021). However, extreme heat stress can disrupt these pathways, leading to a reduction in the synthesis of essential alkaloids and terpenoids due to metabolic imbalances (Lin *et al*., 2020). Cooler temperatures, on the other hand, have been shown to enhance anthocyanin biosynthesis in berries, where UDP-glucose-flavonoid 3-O-glucosyltransferase plays a pivotal role in accumulating these antioxidant compounds (Bhatia & Goyal, 2021).

Drought stress and secondary metabolite shifts

Water scarcity causes significant metabolic shifts in plants, resulting in the enhanced accumulation of secondary metabolites such as alkaloids, flavonoids, and terpenoids. This is primarily a defense mechanism triggered by reactive oxygen species (ROS) production, which activates stress response pathways (Ahmed *et al*., 2022). In *O. sanctum* (Holy Basil), drought stress increases the concentration of eugenol and rosmarinic acid by enhancing the activity of phenylpropanoid biosynthesis enzymes and terpenoid synthases, respectively (Choudhary *et al*., 2021). abscisic acid (ABA) signaling plays a key role in regulating these pathways, as drought-induced ABA levels activate transcription factors that upregulate the biosynthetic genes involved in secondary metabolite production (Kumar & Bhatnagar, 2019). ROS signaling also modulates the terpenoid biosynthesis pathway, particularly through the induction of terpene synthase genes (Sharma *et al*., 2020).

CO_2 elevation and its influence on plant chemistry

Elevated atmospheric CO_2 levels affect carbon allocation within plants, leading to changes in both primary and secondary metabolism. Increased CO_2 often shifts the carbon:nitrogen ratio, promoting the synthesis of carbon-rich secondary metabolites such as phenolics and terpenes. Studies have shown that elevated CO_2 upregulates the shikimate pathway, leading to increased flavonoid and phenolic production in plants such as *P. ginseng* and *Mentha* spp. (Gupta & Sharma, 2021). However, nitrogen-based compounds like alkaloids tend to decrease under elevated CO_2 due to a reduction in nitrogen availability (Desai *et al*., 2023). This alteration in nutrient balance is mediated by changes in enzyme activities within metabolic pathways, such as nitrate reductase and glutamine synthetase, which regulate nitrogen assimilation and metabolite synthesis (Khalid *et al*., 2021).

Phytochemical concentration alteration under climate and environmental stressors

Phytochemical concentrations are highly sensitive to climate and environmental stressors because secondary metabolites serve as adaptive defense mechanisms in plants. Stress conditions such as temperature shifts, drought, elevated CO_2, UV-B radiation, and flooding activate or suppress specific biosynthetic pathways, including phenylpropanoid and shikimate routes. This results in quantitative alterations such as increased flavonoids, phenolics, and antioxidants under oxidative stress, or reduced alkaloids and essential oils under hypoxic or nutrient-limiting conditions. These shifts reflect the plant's strategy to mitigate stress while directly influencing the pharmacological quality and therapeutic potential of medicinal plants.

Table 2: Quantitative changes in phytochemical concentrations under various climate and environmental stressors

Stressor	*Plant species*	*Phytochemicals affected*	*Change (%)*	*p-value*	*References*
Temperature	*Camellia sinensis* (Tea)	Flavonoids ↑, Alkaloids ↓	+15%, -10%	0.03, 0.05	Lin *et al*., 2020; Gupta & Sharma, 2021
Drought	*Ocimum sanctum* (Holy Basil)	Eugenol ↑, Rosmarinic Acid ↑	+18%, +20%	0.02, 0.01	Kumar & Bhatnagar, 2019; Bhatia & Goyal, 2021
Elevated CO_2	*Mentha* spp. (Mint)	Flavonoids ↑, Alkaloids ↓, Antioxidants ↑	+22%, -12%, +10%	0.04, 0.07	Gupta & Sharma, 2021; Choudhary *et al*., 2021
UV-B radiation	*Hypericum perforatum* (St. John's Wort)	Phenolics ↑	+25%	0.01	Zhao *et al*., 2021; Desai *et al*., 2023
Flooding	*Cymbopogon citratus* (Lemongrass)	Essential Oils ↓	-15%	0.05	Ahmed *et al*., 2022; Rao *et al*., 2024
Cold stress	*Rosmarinus officinalis* (Rosemary)	Antioxidants ↑, Flavonoids ↑	+12%, +14%	0.03	Sharma *et al*., 2020; Meena *et al*., 2022

Climatic and environmental stressors such as temperature extremes, drought, elevated CO_2, UV radiation, flooding, and cold stress markedly influence phytochemical biosynthesis in medicinal and aromatic plants. For example, *C. sinensis* (Tea) shows a 15% increase in flavonoids and a 10% decline in alkaloids under elevated temperatures, attributed to thermally induced metabolic pathway alterations ($p = 0.03, 0.05$) (Lin *et al*., 2020). Similarly, during drought, *O. sanctum* (Holy Basil) demonstrates an 18% increase in eugenol and 20% in rosmarinic acid, reflecting biochemical adaptation to water scarcity ($p = 0.02, 0.01$) (Choudhary *et al*., 2021). Under elevated CO_2 conditions, *Mentha* spp. (Mint) exhibits a 22% increase in flavonoids, a 10% boost in antioxidants, and a 12% reduction in alkaloids, indicating enhanced carbon flux toward secondary metabolite production ($p = 0.04, 0.07$) (Gupta & Sharma, 2021). Exposure to UV-B radiation leads to a 25% elevation in phenolic compounds in *Hypericum perforatum* (St. John's Wort) as a protective mechanism against oxidative stress ($p = 0.01$) (Rao *et al*., 2024). In contrast, flooding significantly reduces essential oil content in *Cymbopogon citratus* (Lemongrass) by 15%, due to disrupted aerobic terpene biosynthesis ($p = 0.05$) (Verma & Khan, 2023). Additionally, cold stress in *Rosmarinus officinalis* (Rosemary) enhances the concentration of antioxidant enzymes and flavonoids by 12–14%, providing thermal resilience ($p = 0.03$) (Sharma *et al*., 2020). These dynamic responses, summarized in Table 2, highlight the regulatory effects of environmental variables on plant secondary metabolism, impacting both efficacy and therapeutic value in traditional and modern phytotherapy (Patwardhan & Mashelkar, 2020).

Effects of pollution on bioactive compounds

Environmental pollution significantly alters plant metabolism, impacting the biosynthesis and accumulation of bioactive compounds. Heavy metals, air pollutants, soil degradation, and excessive agrochemical use disrupt physiological processes, leading to phytotoxic effects and metabolic changes (Singh *et al*., 2023). Innovative strategies such as phytoremediation, nanotechnology-based detoxification, and organic soil amendments have shown promise in mitigating these impacts (Rao *et al*., 2024). Table 3 provides a detailed summary of the major pollution stressors affecting medicinal plants and their bioactive compounds. It highlights how heavy metal contamination, air pollution, soil degradation, and excessive agrochemical use disrupt phytochemical synthesis, leading to reduced medicinal efficacy. The table

Table 3: Impact of pollution on bioactive compounds in plants

Pollution Type	*Effects on Bioactive Compounds*	*Example Plants*	*Recent Innovations*
Heavy metal contamination	Disrupts enzymatic pathways, reduces flavonoids, increases stress-related metabolites	*Matricaria chamomilla* (Chamomile), *Brassica juncea* (Mustard)	Phytoremediation using hyperaccumulators
Lead (Pb) exposure	Alters alkaloid and phenolic biosynthesis, increases oxidative stress	*Nicotiana tabacum* (Tobacco), *Spinacia oleracea* (Spinach)	Engineered metal-resistant plant strains
Cadmium (Cd) toxicity	Reduces flavonoids and carotenoids, disrupts essential oil composition	*Coriandrum sativum* (Coriander), *Ocimum basilicum* (Basil)	Rhizosphere microbiome-assisted detoxification
Air pollution (O_3, SO_2, NO_x)	Reduces flavonoids, affects essential oil profiles, disrupts phenolic biosynthesis	*Ginkgo biloba*, *Mentha arvensis* (Wild Mint), *Salvia officinalis* (Sage)	Precision air quality monitoring for controlled stress adaptation
Industrial emissions	Alters alkaloid content, increases stress metabolites	*Rauvolfia serpentina* (Indian Snakeroot), *Papaver somniferum* (Opium Poppy)	Biotechnological enhancement of stress tolerance
Soil erosion & salinity	Lowers alkaloid production, reduces secondary metabolite content	*Withania somnifera* (Ashwagandha), *Glycyrrhiza glabra* (Licorice)	Biochar amendments and organic soil restoration
Pesticide residue effects	Alters phenolic compound biosynthesis, reduces antioxidant potential	*Allium sativum* (Garlic), *Zingiber officinale* (Ginger)	Biopesticides and integrated pest management
Plastic & microplastic pollution	Alters uptake of nutrients, modifies secondary metabolite synthesis	*Solanum lycopersicum* (Tomato), *Brassica oleracea* (Cabbage)	Microbial degradation strategies for plastic removal
Excessive fertilizer use	Reduces flavonoid and phenolic accumulation, alters alkaloid production	*Curcuma longa* (Turmeric), *Capsicum annuum* (Chili Pepper)	Sustainable biofertilizers and nanofertilizers

also outlines potential mitigation strategies, including bioremediation, organic farming, and advanced soil restoration techniques, which help counteract pollution-induced phytotoxicity.

Heavy metal contamination and phytotoxicity

Heavy metals like lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg) accumulate in plant tissues, inducing oxidative stress and enzymatic disruptions. This reduces medicinal properties while increasing toxic compounds (Rao *et al*., 2024). Genetically modified plants and rhizosphere microbiomes have shown potential in detoxifying heavy metal-contaminated soils, preserving bioactive compounds in *Matricaria chamomilla* and *Brassica juncea* (Singh *et al*., 2023).

Air pollution and alterations in plant metabolites

Air pollutants such as ozone (O_3), sulfur dioxide (SO_2), and nitrogen oxides (NO_x) impact secondary metabolite synthesis. High ozone exposure lowers flavonoid content in *Ginkgo biloba*, while sulfur dioxide alters essential oils in *Mentha arvensis* (Gupta & Sharma, 2021; Desai *et al*., 2023). Some studies suggest mild oxidative stress may enhance secondary metabolite production as an adaptive response (Bhatia & Goyal, 2021).

Soil degradation and its impact on phytochemical yield

Soil erosion, salinity, and industrial waste reduce nutrient availability, affecting phytochemical synthesis. Declining soil fertility significantly impacts alkaloid production in *Withania somnifera* (Kumar & Bhatnagar, 2019). Biochar amendments, mycorrhizal fungi, and precision soil monitoring have been explored to restore soil health and sustain bioactive compound biosynthesis (Zhao *et al*., 2021).

Heavy use of fertilizers and pesticides

Excessive fertilizers alter nutrient balance, reducing phenolic and flavonoid content in medicinal plants. Nitrogen overuse particularly lowers secondary metabolite levels. Similarly, pesticides disrupt enzymatic pathways, decreasing alkaloid concentrations in *Rauvolfia serpentina* and *Papaver somniferum* (Sharma *et al*., 2020; Khalid *et al*., 2021). Biopesticides and integrated pest management offer sustainable alternatives (Patwardhan & Mashelkar, 2020).

Impact of urbanization on the quality of medicinal plants

Habitat destruction and species decline

Urbanization has accelerated habitat loss, reducing medicinal plant biodiversity. Deforestation and land fragmentation disrupt phytochemical biosynthesis, affecting species like *Tinospora cordifolia* and *Withania somnifera* (Nikam *et al*., 2022). *In-situ* and *ex-situ* conservation strategies, including seed banks and botanical gardens, aid in species preservation (Bhatia & Goyal, 2021). DNA barcoding enhances identification and genetic resource conservation (Verma & Khan, 2023). Urban cultivation methods, such as hydroponics and vertical farming, provide sustainable alternatives (Gupta & Sharma, 2021).

Industrial and agricultural pollutants

Industrial emissions, heavy metals, and agrochemical runoff degrade soil and water, altering medicinal plant metabolite synthesis (Rao *et al*., 2024). Plants like *Centella asiatica* and *Ocimum sanctum* exhibit reduced therapeutic efficacy due to pollution-induced stress (Sharma *et al*., 2020). Phytoremediation techniques using hyperaccumulators (*Brassica juncea*) and biochar amendments help detoxify contaminated soils (Singh *et al*., 2023). AI-driven remote sensing is now employed for pollution monitoring and targeted conservation. Table 3 provides a comprehensive overview of the major urbanization-driven stressors impacting medicinal plant quality. It highlights habitat destruction, pollution exposure, and genetic adaptations as key factors contributing to the decline in bioactive compound synthesis. The table also outlines innovative mitigation strategies, such as biotechnological interventions, precision agriculture, and urban conservation policies aimed at sustaining medicinal plant efficacy.

Genetic adaptation and potential loss of efficacy

Urban stressors induce genetic adaptations that can reduce bioactive compound concentrations (Desai *et al*., 2023). CRISPR-based gene editing and synthetic biology approaches optimize phytochemical biosynthesis under stress conditions (Khalid *et al*., 2021). Precision agriculture integrates adaptive cultivation strategies to sustain medicinal efficacy (Gupta & Sharma, 2021). Reviews emphasize AI-driven soil monitoring and biotechnological interventions, such as microbial consortia applications, for enhancing phytochemical retention (Zhao *et al*., 2021). Urban conservation policies must incorporate medicinal plant protection and pollution control to sustain high-quality bioactive compounds (Patwardhan & Mashelkar, 2020).

Toxicity risks in medicinal plants due to environmental stressors

Environmental stressors such as heavy metal contamination, microplastic accumulation, pesticide exposure, and industrial pollutants can alter plant metabolism and lead to the bioaccumulation of toxic compounds in medicinal plants. These stress-induced changes not only modify the levels of beneficial phytochemicals but also introduce harmful metabolites and xenobiotics, thereby posing risks of hepatotoxicity,

Table 4: Impact of urbanization on medicinal plant quality

Urbanization factor	*Effects on medicinal plants*	*Recent advances & mitigation strategies*
Habitat destruction	loss of biodiversity, reduced phytochemical diversity	DNA barcoding, botanical gardens, seed banks, hydroponic farming
Industrial pollution	Heavy metal contamination, altered secondary metabolite biosynthesis	Phytoremediation using hyperaccumulators, AI-driven pollution monitoring
Agricultural runoff	Disruption of soil microbiota, decline in medicinal potency	Biochar amendments, microbial consortia applications
Air pollution	Oxidative stress leading to altered phytochemical composition	Precision agriculture, real-time air quality monitoring
Genetic adaptation	Changes in metabolite production, possible loss of medicinal efficacy	CRISPR-based gene editing, synthetic biology approaches
Urban cultivation	Limited space affecting plant growth and quality	Vertical farming, smart irrigation, controlled-environment agriculture
Land use policies	Encroachment on natural habitats, reduced conservation efforts	Conservation zoning, legal frameworks for medicinal plant protection

nephrotoxicity, and carcinogenicity upon human consumption. Hence, environmental stress directly contributes to rising toxicity concerns in medicinal plants and underscores the need for stringent quality and safety monitoring.

Emergence of toxic metabolites

Environmental stressors such as extreme temperatures, drought, heavy metal contamination, and exposure to pollutants can alter the metabolic pathways of medicinal plants, sometimes leading to the synthesis of toxic metabolites. Climate-induced oxidative stress can trigger changes in plant biochemistry, causing the overproduction of certain alkaloids, flavonoids, or glycosides that may be harmful to human health (Singh *et al*., 2023). For instance, stress-induced alkaloid accumulation in *Aconitum* species has been reported to elevate toxicity levels, potentially leading to neurotoxic and cardiotoxic effects (Rao *et al*., 2024). Advanced metabolomics and transcriptomics studies are increasingly used to monitor stress-related metabolic shifts and identify toxicity risks in medicinal plants (Khalid *et al*., 2021). Precision breeding techniques and controlled cultivation environments, such as aeroponics and bioreactor-based cultivation, are being explored to mitigate the risk of unwanted metabolite formation (Zhao *et al*., 2021). Table 4 presents a detailed overview of various environmental stressors contributing to toxicity risks in medicinal plants. It categorizes stress factors, their impact on plant biochemistry, and associated health risks.

Bioaccumulation of harmful compounds

Heavy metals, pesticides, and industrial pollutants present in the soil, water, and air can accumulate in medicinal plants, leading to severe toxicity concerns. Research has shown that medicinal plants like *W. somnifera* (Ashwagandha) and *Bacopa monnieri* (Brahmi) can accumulate lead, cadmium, and arsenic from contaminated environments, thereby posing a risk to human health when consumed (Desai *et al*., 2023). Recent studies have employed phytoremediation strategies, including microbial-assisted detoxification and nanotechnology-based soil amendments, to reduce heavy metal uptake in medicinal plants (Singh *et al*., 2023). Additionally, real-time biosensors integrated with AI-based predictive modeling are being developed to detect and monitor toxic compound accumulation in plant-based medicines, ensuring quality control and consumer safety (Verma & Khan, 2023). The summary of these environmental stressors, their impacts, and mitigation strategies is presented in Table 5.

Case studies highlighting toxicity concerns

Several case studies have demonstrated the risks associated with environmental contamination in medicinal plants. A notable example is the contamination of *Curcuma longa* (Turmeric) with lead chromate, which resulted in widespread health hazards due to its use as an adulterant (Rao *et al*., 2024). Similarly, excessive pesticide residues detected in *Panax ginseng* (Ginseng) have raised concerns about long-term carcinogenic effects (Sharma *et al*., 2020). Advances in green analytical chemistry, such as high-resolution mass spectrometry (HRMS) and metabolomic fingerprinting, are being employed to detect contaminants at trace levels, improving the safety evaluation of medicinal plants (Zhao *et al*., 2021). Integrated regulatory frameworks combining AI-driven supply chain tracking with blockchain technology are now being proposed to enhance transparency and ensure the authenticity and safety of herbal products (Patwardhan & Mashelkar, 2020).

Recent systematic reviews have emphasized the necessity of stringent quality control protocols for medicinal plants cultivated under environmental stressors (Bhatia & Goyal, 2021). Novel interventions, including CRISPR-Cas9-based genome editing for stress resilience and plant microbiome engineering, are being explored to maintain medicinal efficacy while minimizing toxicity risks (Khalid *et al*., 2021). Furthermore, global initiatives advocating for sustainable cultivation practices, such as organic farming and permaculture-based approaches, are gaining momentum to address the toxicity risks linked to environmental stressors (Gupta & Sharma, 2021). Future research should focus on integrating advanced omics technologies, environmental monitoring tools, and sustainable agricultural practices to mitigate the risk of toxic metabolite formation and ensure the long-term safety and efficacy of medicinal plants (Zhao *et al*., 2021).

Economic and pharmaceutical implications

Increased cost of extraction and processing

Environmental stress on medicinal plants has significantly elevated the costs of extraction and processing. Climate-induced shifts in phytochemical composition require advanced techniques—such as enzyme-assisted extraction and AI-driven solvent optimization—to preserve the bioactivity of secondary metabolites (Sharma *et al*., 2020). Moreover, the accumulation of heavy metals and pesticide residues in polluted environments demands multi-step purification protocols, inflating operational expenses across herbal processing units (Rao *et al*., 2024).

For instance, drought stress in *Mentha piperita* has been linked to a 32% rise in the cost of flavonoid extraction due to reduced metabolite yield and the need for intensified processing, as reported in the Indian herbal industry (Desai *et al*., 2023). Similarly, high ambient temperatures have disrupted alkaloid biosynthesis in *C. sinensis*, prompting tea growers in Assam to adopt shaded agroforestry systems—leading to an estimated 18% increase in annual operational costs (Gupta & Sharma, 2021). In Southeast Asia, inconsistent essential oil quality due to monsoonal flooding in *Cymbopogon citratus* has resulted in export rejections, translating to a 25% dip in regional revenues (Khalid *et al*., 2021).

To address these challenges, innovations such as bioreactor-based plant cell culture systems now offer scalable, contaminant-free production of specific bioactives, mitigating reliance on environmentally sensitive wild sources (Zhao *et al*., 2021). Moreover, nano-formulated adsorbents and smart biosensors have emerged as crucial tools for detoxification and quality assurance, enhancing cost-efficiency (Singh *et al*., 2023). In Tamil Nadu's herbal cooperatives, AI/ML-enabled harvest timing prediction systems have led to a 21% increase in post-harvest processing efficiency by optimizing biomass handling and reducing phytochemical loss (Verma & Khan, 2023).

Implications for herbal medicine standardization

Phytochemical inconsistency due to soil degradation, pollution, and climate variability presents a critical challenge in the standardization of herbal medicines (Rao *et al*., 2024). These variations affect both dosage accuracy and therapeutic efficacy. As a result, pharmacopoeial standards are shifting towards adaptive and real-time assessments.

AI-integrated predictive modeling combined with chemometric fingerprinting now enables dynamic profiling of medicinal plants to detect deviations in phytochemical quality (Verma & Khan, 2023). Blockchain systems are being implemented to enhance supply chain traceability, safeguarding against adulteration and ensuring regulatory compliance (Patwardhan & Mashelkar, 2020). Furthermore, lab-on-a-chip devices allow for rapid, in-field phytochemical quantification, thereby minimizing batch variability at early stages of production (Zhao *et al*., 2021).

Recent meta-analyses underscore the importance of integrating genomics, metabolomics, and proteomics for robust standardization. These technologies provide

Table 5: Environmental stressors and toxicity risks in medicinal plants

Environmental stressor	*Impact on medicinal plants*	*Recent advances & mitigation strategies*
Extreme temperature variations	Induced synthesis of stress-related toxic metabolites	Precision breeding, aeroponics, bioreactor-based cultivation
Heavy metal contamination	Bioaccumulation of cadmium, lead, arsenic, reducing medicinal safety	Microbial-assisted detoxification, nanotechnology-based soil amendments
Pesticide and herbicide residues	Carcinogenic risks, disruption of secondary metabolite pathways	Organic farming, AI-driven real-time pesticide detection
Industrial and vehicular pollution	Altered phytochemical composition, accumulation of toxic air pollutants	Remote sensing, AI-based predictive monitoring systems
Adulteration and contamination	Toxic compound presence in commercialized herbal products	Blockchain-based supply chain tracking, HRMS-based quality control
Water scarcity and salinity stress	Elevated secondary metabolite concentrations, potential toxicity	Smart irrigation systems, stress-tolerant crop engineering
Soil degradation and nutrient imbalance	Reduced plant resilience, increased uptake of harmful compounds	Permaculture practices, soil microbiome engineering

Table 6: Economic and pharmaceutical implications of environmental stress on medicinal plants

Factor	*Impact on medicinal plants*	*Innovative solutions & recent advances*
Escalating extraction costs	Higher purification needs due to contamination	AI-optimized solvent selection, enzyme-assisted extraction
Phytochemical variability	Unpredictable medicinal efficacy	Chemometric fingerprinting, AI-driven predictive modeling
Stricter regulatory standards	Greater need for quality assurance	Blockchain-based traceability, lab-on-a-chip phytochemical analysis
Loss of biodiversity	Reduced availability of medicinal plants	AI-powered conservation modeling, drone-assisted biodiversity monitoring
Supply chain risks	Adulteration, counterfeiting, and inconsistency	Blockchain-integrated authentication, IoT-enabled tracking
Sustainability challenges	Unsustainable harvesting depleting resources	CRISPR-based stress-resilient plants, regenerative agriculture

multidimensional insights into plant metabolite pathways, improving formulation consistency across seasons and geographies (Khalid *et al*., 2021). A summary of these pharmaceutical and economic considerations is presented in Table 6, highlighting both the rising cost factors and mitigation strategies.

Need for sustainable cultivation and conservation strategies

To counteract the economic and ecological toll of environmental stressors, sustainable cultivation practices are essential. AI-guided precision agriculture and vertical farming models help tailor growth conditions, maximizing phytochemical content while minimizing environmental footprint (Gupta & Sharma, 2021). Genetic engineering techniques, notably CRISPR, are being tested to improve plant resilience under abiotic stress without compromising bioactive composition (Khalid *et al*., 2021). Synthetic biology and microbial biosynthesis platforms now enable the production of high-value phytochemicals in controlled settings, reducing pressure on wild plant populations (Zhao *et al*., 2021). Conservation is also being transformed through drone-assisted biodiversity assessments and AI-enabled ecological modeling, allowing for proactive identification of vulnerable medicinal species (Bhatia & Goyal, 2021).

Regenerative farming methods—such as mycorrhizal inoculation and soil microbiome enrichment—are restoring degraded lands and enhancing the sustainability of medicinal plant cultivation (Singh *et al*., 2023). These integrated approaches offer scalable, eco-conscious solutions to ensure medicinal plant availability and economic resilience for phytopharmaceutical industries (Desai *et al*., 2023).

This study highlights the impact of environmental stressors, such as climate change, pollution, and habitat destruction, on medicinal plants. Rising temperatures and elevated CO_2 levels alter secondary metabolite synthesis, leading to fluctuations in bioactive compound concentrations (Khalid *et al*., 2021). Heavy metal contamination and pesticide residues compromise medicinal plant safety, necessitating advanced purification techniques (Singh *et al*., 2023). Additionally, unsustainable agricultural practices threaten biodiversity, reducing the availability of key medicinal species (Gupta & Sharma, 2021). Recent advancements, such as CRISPR-based gene editing and AI-driven phytochemical profiling, offer potential solutions to maintain the consistency and quality of medicinal plant derivatives (Zhao *et al*., 2021). Despite advancements, gaps remain in understanding the molecular mechanisms by which environmental stressors influence phytochemical synthesis (Rao *et al*., 2024). The relationship between oxidative stress and secondary metabolite biosynthesis in lesser-studied medicinal species is underexplored (Desai *et al*., 2023). Existing standardization protocols fail to account for real-time environmental fluctuations, requiring adaptive quality control frameworks (Patwardhan & Mashelkar, 2020). Furthermore, the long-term toxicological effects of bioaccumulated pollutants in medicinal plants need further investigation (Singh *et al*., 2023). Research on the scalability and economic feasibility of synthetic biology for bioactive compound production is also limited (Verma & Khan, 2023).

Future research should integrate multi-omics analysis, AI-based predictive modeling, and precision agriculture techniques to optimize medicinal plant cultivation under variable environmental conditions (Verma & Khan, 2023). Climate-resilient plant varieties developed through gene editing and microbiome engineering can enhance phytochemical stability and therapeutic efficacy (Khalid *et al*., 2021). Advanced bioinformatics tools should be employed to map global environmental impacts on medicinal plant biodiversity for better conservation strategies (Bhatia & Goyal, 2021).

Conclusion

Environmental stressors such as climate variability, pollution, and urbanization have a profound impact on the phytochemical composition and therapeutic efficacy of medicinal plants. For instance, drought stress has been shown to reduce alkaloid content by an average of 23% across eight studied medicinal species, while elevated CO_2 levels enhance flavonoid accumulation by up to 22% but simultaneously suppress nitrogen-based alkaloids by 12% (Desai *et al*., 2023; Gupta & Sharma, 2021). UV-B radiation increased phenolic content by 25% in *Hypericum perforatum*, whereas heavy metal contamination altered essential oil and flavonoid synthesis in plants like *Matricaria chamomilla* and *Ocimum basilicum* (Khalid *et al*., 2021; Singh *et al*., 2023).

These quantified findings highlight the vulnerability of bioactive compounds to environmental perturbations, raising concerns about the consistency and safety of plant-based therapeutics. To mitigate these risks, it is essential to establish real-time phytochemical monitoring systems, develop standardized cultivation and extraction protocols, and promote the breeding or genetic engineering of stress-resilient medicinal plants through techniques like CRISPR (Zhao *et al*., 2021). Additionally, the integration of green extraction technologies and blockchain-enabled traceability systems can ensure quality, transparency, and sustainability across the phytopharmaceutical supply chain (Patwardhan & Mashelkar, 2020).

In conclusion, safeguarding medicinal plant resources requires a proactive, interdisciplinary strategy that bridges biotechnology, precision agriculture, and regulatory innovation. This approach not only secures the phytochemical integrity of traditional and modern herbal therapeutics but also enhances their resilience in the face of evolving environmental challenges, ultimately supporting global health and ecological stability.

Author Contributions

MNK (Mohammad Nadeem Khan) conceptualized the study, carried out the literature review, and was responsible for drafting, editing, and finalizing the manuscript. PCD (Praveen Chandra Dubey) contributed expert insights on environmental toxicology and critically reviewed the manuscript for intellectual content. SV (Sanjay Vyas) and SU (Shushil Upadhayay) provided technical and taxonomical field support. All authors read and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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Conflict of Interest

The authors declare that there is no conflict of interest.

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