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Review Article

The Unseen Patient: Effect Of Climate Change on Medicinal Plant Efficacy

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ABSTRACT

This review explains a critical yet underappreciated side of the global climate crisis. Its profound impact on medicinal plants, which serve as a cornerstone of healthcare for billions worldwide. By synthesizing contemporary scientific evidence, we delineate how climate-induced stressors such as elevated temperatures, altered precipitation patterns, and extreme weather events disrupt the complex biochemical pathways of these essential species. Our analysis confirms that such environmental pressures can reduce the concentration of bioactive secondary metabolites, including alkaloids, flavonoids, and terpenes, or induce unpredictable variations in their biosynthesis, thereby compromising therapeutic efficacy. Moreover, climate change impairs anthropogenic threats, such as overharvesting and habitat degradation, accelerating widespread habitat loss for vulnerable species. This synergistic interaction not only risks global health by declining the availability and reliability of plant-derived medicines but also threatens the erosion of irreplaceable traditional knowledge systems, painstakingly developed over millennia by indigenous and local communities. Consequently, we declare that the climate-driven decline of nature's pharmacy constitutes an urgent threat to global health security and cultural heritage. To address this crisis, we advocate for a coordinated, multi-disciplinary approach that integrates advanced scientific research, sustainable agricultural and conservation practices, and equitable collaboration with original knowledge holders to ensure the preservation of these vital resources for future generations.

INTRODUCTION

Medicinal plants are a vital part of healthcare. They form the basis for traditional remedies and provide active compounds for many modern

medicines. The effectiveness of these plants depends on the right concentration and balance of their bioactive secondary metabolites, such as alkaloids, flavonoids, and terpenes. This important chemical balance has developed over thousands of

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years in response to specific environmental conditions. However, global climate change is now unruly this balance in significant ways. Changes in temperature, atmospheric carbon dioxide (CO₂) levels, rainfall patterns, and more frequent extreme weather events are all affecting plant physiology and thus, their medicinal quality.

It is essential to understand these complex effects for the future of global healthcare, drug development, and plant biodiversity conservation. For thousands of years, these plants have reinforced human health by forming the basis of traditional medicines and modern drugs. About 80% of the world's population relies on plant-based remedies, especially in developing areas. However, climate change driven by human activities, creates stressors that disrupt plant physiology, distribution, and chemical composition. These changes not only affect plant availability but also their effectiveness, putting treatments for various diseases, from inflammation to cancer, at risk. This paper brings together evidence from scientific studies to explain these effects.

Mechanistic Pathways of Climate Change Impact on Medicinal Plants²

Climate change exerts influence on medicinal plant species through a crowd of interconnected physiological, biochemical, and ecological pathways, ultimately affecting their therapeutic potency and availability. The primary mechanisms are as follows:

- **Variations in Biosynthetic Pathways:** The production of bioactive secondary metabolites is intense to environmental conditions. Elevated atmospheric CO₂ can stimulate primary growth through carbon fertilization, yet this frequently results in a dilution effect, whereby the concentration of vital

phytochemicals is reduced. Conversely, abiotic stressors—including drought, extreme temperatures, and sharp UV-B radiation—can induce defensive physiological responses. This may lead to an upregulation in the synthesis of certain secondary metabolites (e.g., flavonoids, alkaloids); however, these outcomes are especially species-specific and non-linear, making generalized predictions.

- **Changes in Geographic Distribution and Habitat Suitability:** Rising global temperatures are shifting climatic niches, captivating many plant species to migrate to higher latitudes or altitudes to track suitable habitats. This poses a significant threat to species with limited adaptive capacity or dispersal mechanisms, endangering genetic diversity and leading to potential local extinctions. Consequently, the sustainable availability of wild-harvested medicinal resources is severely compromised, with direct implications for both traditional medicine systems and bioprospecting efforts.
- **Disturbances in Species Interactions:** Climate change modifies the dynamics of biotic interactions. Warmer temperatures can expand the range and virulence of pests and pathogens, subjecting plants to increased biotic stress that can compromise their health and chemical profile. Furthermore, phenological mismatches such as a desynchronization between a plant's flowering period and the activity cycle of its specialized pollinators can disrupt reproductive success, impairing seed set and long-term population viability.
- **Compromised Harvest Quality and Post-Harvest Integrity:** The optimal harvest time, critical for maximizing phytochemical yield, is determined by precise environmental signs.



Increasingly frequent extreme weather events (e.g., unseasonal droughts, floods) can disrupt plant development and displace this optimal window, leading to harvests with sub-therapeutic compound levels. Post-harvest, fluctuations in ambient temperature and humidity can accelerate the degradation of sensitive bioactive molecules, further fading the efficacy and shelf-life of the raw material.

Examples

- ***Gentiana rigescens***: Climate projections show severe habitat loss, leads to lower iridoid
- glycoside content and reduced medicinal quality.
- **Aloe vera**: Salinity and drought alter phenolic content and antioxidant activity, with mixed efficacy rate.
- ***Hypericum perforatum* (St. John's Wort)**: Stress conditions change active ingredient profiles, influencing its use for depression treatment.
- **American ginseng and goldenseal**: Declines due to warming, overharvesting, and disrupted ecosystems threat.

Compound Class	Examples/Therapeutic Use	Typical Effect of Drought	Typical Effect of Elevated CO ₂	Typical Effect of Heat Stress
Terpenes	Artemisinin (Antimalarial), Menthol (Decongestant)	Response is variable, sometimes increasing	Often increases (Carbon-based)	Often decreases
Phenolics	Curcumin (Anti-inflammatory), Silymarin (Liver protectant)	Frequently increases (Antioxidant defense)	Frequently increases (Carbon-based)	Variable response
Alkaloids	Morphine (Analgesic), Vincristine (Anticancer)	Frequently decreases (Nitrogen limitation)	Often decreases (Dilution/N allocation)	Frequently decreases
Glycosides	Senna glycosides (Laxative), Cardiac glycosides (Heart)	Frequently decreases	Variable response	Frequently decreases
Essential Oils	Complex mixtures (Antimicrobial, Relaxant)	Often increases, Altered Composition	Variable response (Yield/Composition)	Often decreases Yield & Quality

Changes in Bioactive Compounds and Efficacy¹

The healing power of medicinal plants comes from their active ingredients, like alkaloids, flavonoids, terpenoids, and phenolics. However, climate changes, such as rising temperatures or drought, can disrupt these compounds, making the plants less effective or unpredictable. For instance, hotter and drier conditions might reduce flavonoids and

phenolic acids, which weakens the plant's ability to fight inflammation or act as an antioxidant. On the flip side, some plants adapt to stress by producing more of certain compounds like aloe vera, which induce aloin production under salty conditions, boosting its anti-inflammatory effects, even if its overall phenolic content drops.



But these changes aren't always good enough. Stress can also cause plants to produce more toxic compounds, like pyrrolizidine alkaloids, which can be harmful to people using them. This variability makes it tough to create consistent, reliable herbal medicines, raising concerns about their safety and effectiveness.

The Bio-Ecological Crisis: Habitat Contractions and Range Shifts

Climate change is forcing a profound modification of ecosystems, compelling medicinal plant species to migrate to higher altitudes and latitudes in search of suitable habitats. For many, this migration is not fast enough or is geographically impossible due to natural barriers or human-altered landscapes.

- An example of this is *Gentiana rigescens*³⁷, an economically important medicinal plant in Southwest China¹. Climate projections indicate a severe threat to its survival, with projections showing a decline of up to 99% of its highly suitable habitat by 2070 under high-emission climate situations. This reduction in optimal habitat associates directly with a decline in the medicinal quality of the plant, as samples from less suitable areas contain lower concentrations of key iridoid glycosides. This ecological vulnerability is not an isolated problem but is compounded by other anthropogenic and environmental stressors, creating a synergistic effect that accelerates species decline.
- American ginseng³⁸ (*Panax quinquefolius*) serves as a powerful illustration of this phenomenon. The species is already under significant pressure from overharvesting and habitat loss due to logging, which has reduced many populations from hundreds to mere dozens of plants. At the same time, American

ginseng is highly sensitive to changes in temperature and precipitation. Research indicates that its growth and the accumulation of its therapeutic ginsenosides are detrimentally affected by insufficient winter chilling and excessively high summer temperatures. Thus, a wild population, already weakened by unsustainable harvesting, becomes far less resilient to the added stress of a warming climate. The effect is not merely additive; a depleted population's risk of local extinction is amplified by climate variability, creating a "perfect storm" of threats. This same compounding vulnerability is evident in the frankincense-producing

- *Boswellia* trees³⁹, where overexploitation to meet global demand is exacerbated by climate-induced increases in temperature and decreased precipitation in their arid native habitats, threatening the species with near extinction in some regions within the next three decades.

Altered Phytochemistry: From Environmental Stress to Chemical Variability

The crisis extends beyond a plant's physical presence to its very chemical composition. Environmental stressors like drought, salinity, and temperature extremes act as elicitors, triggering complex biochemical responses that can alter the production and accumulation of secondary metabolites. These compounds, which are often the active ingredients in medicinal plants, are typically biosynthesized as a defence mechanism against stress. However, this adaptive response can have unpredictable consequences for their medicinal value. The effects are not uniform and can be contradictory.

- *Gentiana rigescens*: A Case of Imminent Habitat Loss



Gentiana rigescens is an economically important medicinal plant in southwest China, where it is used in traditional medicine and provides compounds for various Chinese patent drugs. However, this species faces an existential threat from climate change and over-harvesting, which has already led to its classification as Endangered. Research using maximum entropy modeling has simulated the effect of climate change on its distribution, revealing a startling vulnerability. Under high-emission climate scenarios (Representative Concentration Pathway 8.5), projections indicate a staggering loss of up to 99% of its highly suitable habitat by 2070. This habitat contraction is directly correlated with a decline in medicinal quality, as plants from less-than-optimal areas contain lower concentrations of key iridoid glycosides. This case study serves as a stark example of how habitat loss can directly translate into a loss of therapeutic value, threatening both the species and the industry that relies upon it.

➤ **American Ginseng and *Boswellia* species: A Study in Compounding Stressors**

For many plants, climate change is not the sole cause of their decline but rather a powerful accomplice. *American ginseng* (*Panax quinquefolius*) aids as a moving illustration of this dynamic. The species is already under significant pressure from overharvesting and habitat loss due to logging, which has reduced many populations to a fraction. Simultaneously,

American ginseng is sensitive to climate variability. Research indicates that its growth and the accumulation of its therapeutic ginsenosides are detrimentally affected by insufficient winter chilling and excessively high summer temperatures. An already depleted and vulnerable population is thus far less resilient to the added stress of a warming climate, amplifying the risk of

local extinction. This combining vulnerability is obvious in the frankincense-producing

Boswellia trees, where overexploitation to meet global demand is worsened by climate-induced increases in temperature and decreased precipitation in their native arid habitats, threatening the extincting species in some regions within the next three decades.

➤ **The Chemistry between *Aloe vera* and *Hypericum perforatum***

Climate change introduces a fundamental unpredictability into the phytochemistry of medicinal plants. This is demonstrated by species whose responses to stress are non-linear and at times, self-contradictory. The study says *Aloe vera* show that while severe drought stress can reduce total phenolic content and antioxidant activity, a similar level of stress in a different study increased the production of aloin, a potent anti-inflammatory agent. The plant's adaptive responses can have unpredictable consequences.

Similarly, the chemical profile of *Hypericum perforatum* (St. John's Wort), a plant widely used to treat depression, is significantly altered by environmental incentives. For instance, cold adaptation has been shown to decrease the number of key compounds such as hypericin. This biochemical variability means that a plant from one location or a particular harvest year may have a massively different chemical fingerprint than one from another location or year. It introduces a fundamental lack of consistency that threatens the efficacy of traditional medicine and complicates the standardization of modern herbal products. The pharmacological effect is no longer a fixed characteristic but a dynamic response to the plant's environment.



The challenge is a plant's chemical profile is no longer having a fixed characteristic but a dynamic response to its environment. The "same" plant species harvested after a severe drought condition may have a vastly different chemical fingerprint

than one harvested in a normal year. This biochemical variability moves beyond simple quality decline to introduce a fundamental unpredictability in a product's therapeutic outcome.

Plant Species	Key Bioactive Compounds	Climate Stressor	Observed Effect
<i>Gentiana rigescens</i>	Iridoid glycosides (e.g.gentiopicroside)	Habitat decline, Temperature	Reduced concentration in less-than-optimal habitats; 99% habitat loss projected.
<i>Aloe vera</i>	Phenolics, Flavonoids, Aloin	Drought, Salinity	Mixed effects; can increase phenolic content under mild stress or reduce it under severe stress.
<i>Hypericum perforatum</i>	Hypericin, Hyperforin, Flavonoids	Temperature, Drought	Stress conditions can redirect metabolism and alter the accumulation of these compounds.
American Ginseng	Ginsenosides	Temperature, Photoperiod	Insufficient winter chilling and high temperatures inhibit growth and ginsenoside accumulation.
<i>Boswellia</i> species	Resins, Terpenoids	Increases temperature, decreases precipitation	Leads to habitat loss and reduced resin production and quality

Threats to Human Health and Traditional Knowledge Systems

Climate change severely affects the health of vulnerable communities. It creates a critical dependence on resources that are also being harmed. In places like Bangladesh²¹, where people are especially sensitive to impulsive weather, an increase in climate-sensitive diseases such as malaria, dengue, and dysentery has been recorded. With limited access to affordable modern medicine, these communities are increasingly count on on traditional herbal remedies for health support. This sets up a harmful cycle. The communities experiencing increasing health

challenges due to climate change are the same ones whose primary sources of medicine are degrading by the same issue. The rising demand for traditional medicine is not matched by an adequate supply of plants, which are becoming unusual and weaker, exposing the health security of populations across Asia and Africa.

This systemic threat also leads to the loss of valuable cultural heritage. For centuries, traditional knowledge¹⁸ has been deeply connected to the local environment and the specific characteristics of plants. As climates change and plant behaviours fluctuate, this detailed knowledge risks becoming outdated and forgotten. Indigenous

communities in North America and Nepal illustrate this cultural loss. A study highlights how a traditional "bread dance" ceremony, which is meant to align with a particular stage of a tree's leaf growth, is now disrupted by climate-related changes in plant development. A tribal practitioner mentions a "false" harvestable product from a tobacco plant due to drought, as well as a sourberry bush that produces seedless berries, turning the traditional harvest into a hollow ritual. These incidents are more than just data points; they represent real experiences that show a serious disruption of the rich, location-specific knowledge passed down through generations. The loss of this oral and practical knowledge threatens the core of cultural identity and resilience, as communities can no longer care for the land and their health as their ancestors once did.

Supply Chain Fragility and Industry Disruption

The global herbal and nutraceutical industry, worth billions of dollars, heavily relies on a stable and consistent supply of high-quality raw plant materials. Climate change directly threatens this foundation. Farmers and wild harvesters are already feeling significant effects. They are dealing with changes in planting and harvest dates, along with reduced harvest volumes and quality. The Iranian saffron yields²² decreasing gradually, which have reportedly splited over the past two decades due to drought conditions and climate-related temperature changes, clearly shows this commercial vulnerability.

The business model of industries, which depends on standardization²⁸, consistency, and consumer trust, is being weakened by climate-driven changes in phytochemicals. Companies aim to provide products with a predictable chemical profile and potency. However, the natural variability of plants harvested from different

locations take years to achieve the goal. This challenge poses a significant issue for regulatory bodies to ensure safe and effective outcomes for patients. As supply chains become less reliable and raw materials grow scarce, the risk of contamination rises as companies struggle to meet the demand. This situation further weakens consumer confidence. Therefore, the industry faces not just a sourcing problem; it provokes a serious threat to its reputation and integrity.

Mitigation and Adaptation Strategies:

To reduce the impacts, strategies include encouraging sustainable farming, protecting habitats, and ex situ conservations like seed banking. Monitoring changes in phytochemicals through research, providing training in sustainable harvesting, and establishing certification programs are essential. Assisted migration may help preserve species, although it requires careful ethical consideration.

- Conservation & Habitat Protection: Establishing and effectively managing protected areas, including migration corridors.
- Sustainable Wild Harvesting⁴³: Implementing strict quotas, rotational harvesting, and certification schemes (like Fair Wild).
- Cultivation (Domestication): Moving production to controlled agricultural settings allows for:
 - Selecting high-yield and high-potency chemotypes.
 - Addressing specific climate stresses (like irrigation and shade houses).
 - Standardizing the material.



- Challenge: Replicating complex wild chemotypes can be challenging, often costly, and not feasible for all species.
- Biotechnological Approaches: Using tissue culture, metabolic engineering, and bioreactors to produce specific compounds outside of climate's influence, although often complicated and costly.
- Seed Banking & Germplasm Conservation²⁶: Preserving genetic diversity for future restoration, breeding, and research.
- Ethnobotanical Research & Community Involvement: Rapidly documenting traditional knowledge and involving local communities in monitoring and conservation efforts (Access and Benefit Sharing - Nagoya Protocol)⁴⁴.
- Climate-Informed Policy: Integrating the vulnerability of medicinal plants into national biodiversity action plans and climate adaptation strategies.

Strategy	Primary Objective	Advantages	Limitations
Seed Banking & Germplasm Conservation	Preservation of genetic diversity	Safeguards species from extinction; provides a genetic resource for future breeding and research.	Does not solve immediate supply chain problems; requires significant long-term funding and infrastructure
Sustainable Wild Harvesting (FairWild)	Conservation and ethical sourcing	Protects wild populations from overexploitation; empowers local communities and preserves traditional knowledge	Dependent on the continued viability of wild habitats, which are threatened by climate change
Controlled Environment Agriculture (CEA)	Consistent, high-yield production	Provides stable growing conditions; ensures predictable quality and potency; can increase bioactive compound concentrations	High capital and operating costs; not economically viable for species with long life cycles or low market value
Biotechnological Approaches	Targeted compound production	Can produce specific compounds independent of climate; high purity and consistency	Often complex and expensive; may fail to replicate the full synergistic profile of whole-plant extracts

CONCLUSION AND STRATEGIC RECOMMENDATIONS

The evidence overwhelmingly demonstrates that climate change is no longer a distant environmental concern but a critical threat actively



reshaping the availability, quality, and efficacy of medicinal plants worldwide. This crisis is a direct challenge to human health, a fundamental disruption to a global industry, and an irreversible assault on the world's cultural heritage.

To address this unfolding crisis, a coordinated, collaborative effort is essential. The following strategic recommendations are imperative for securing the future of this vital resource:

- **For Researchers:** There is an urgent need to accelerate research using advanced omics²⁷ technologies to understand and track the dynamic phytochemical changes occurring in medicinal plants. This research must move beyond single-compound analysis to a holistic, systems-level understanding of how climate stress impacts entire biochemical pathways.
- **For the Herbal Industry:** Companies must invest in resilient, transparent, and traceable supply chains. This includes adopting robust third-party certification standards like Fair Wild for wild-harvested materials and exploring innovative cultivation methods, such as Controlled Environment Agriculture, for vulnerable or high-value species. The future of the industry depends on its ability to guarantee consistent quality and safety to its consumers.
- **For Policymakers:** Governments and international bodies must integrate the vulnerability of medicinal plants into national biodiversity action plans and climate adaptation strategies. This includes allocating resources for *ex situ* conservation through seed banks and protecting indigenous and community rights to traditional knowledge and resources.
- **For Conservationists and Local Communities:** Collaborative, community-led

initiatives are paramount. Efforts must focus on empowering local harvesters, documenting traditional knowledge before it is lost, and implementing sustainable harvesting practices that are scientifically informed and culturally sensitive.

The preservation of medicinal plants is a collective responsibility that requires a multi-disciplinary approach. By combining scientific innovation with cultural wisdom and strategic foresight, it may be possible to secure the future of a resource that is as old as human civilization itself.

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