The Brāhmī, International Multidisciplinary Research Journal
(Peer Reviewed, Referred & Open Access Journal)
Volume: 02 | Issue: 04 | Dec - Feb, 2026 | ISSN: 3048-9660 (Online) | www.thebrahmi.com

Climate Change, Medicinal Plants, and Sustainability: Challenges and Future Pathways

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Introduction

Medicinal plants have been utilized for centuries as a primary source of healthcare and continue to play a vital role in modern medicine. Approximately 80% of the global population depends on traditional plant-based remedies for primary healthcare, particularly in developing countries where access to conventional medical facilities remains limited (WHO, 2019; Chen et al., 2016). These plants are also important sources of bioactive compounds used in the pharmaceutical industry for the development of drugs against cancer, infectious diseases, and chronic disorders (Ekor, 2014; Teoh, 2016). However, climate change has emerged as a significant threat to medicinal plant diversity and sustainability, affecting their distribution, growth, and medicinal properties (IPCC, 2023; Sharma et al., 2020).

Impact of Climate Change on Medicinal Plants

Climate change influences medicinal plants through alterations in temperature, precipitation patterns, and atmospheric carbon dioxide concentrations. These environmental changes can affect species distribution, population dynamics, and ecosystem interactions, leading to shifts in plant communities and increased vulnerability of rare and endemic species (Kunwar et al., 2021; Giam, 2017). Mountain ecosystems are particularly sensitive, with many medicinal plants migrating to higher elevations in response to rising temperatures (Kala, 2015; Sharma et al., 2020).

Effects on Phytochemical Composition

The medicinal value of plants depends largely on their secondary metabolites, including alkaloids, flavonoids, terpenoids, and phenolic compounds. (Isah 2019). Environmental stress induced by climate change can alter the synthesis and accumulation of these bioactive compounds, thereby affecting the therapeutic efficacy and quality of herbal medicines (Selmar & Kleinwächter, 2013; Sharma et al., 2020). Variations in temperature and water availability have been shown to influence the concentration of active constituents in several medicinal plant species, creating challenges for pharmaceutical standardization (Isah, 2019; Ncube et al., 2012).

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Biodiversity Loss and Conservation Challenges

Habitat degradation, overexploitation, invasive species, and climate change collectively contribute to the decline of medicinal plant populations worldwide (Chen et al., 2016; IPBES, 2019). Unsustainable harvesting practices driven by increasing commercial demand have further intensified pressure on wild populations of economically important medicinal plants (Hamilton, 2004; Schippmann et al., 2006). The loss of medicinal plant diversity not only threatens ecosystem stability but also reduces opportunities for future drug discovery and development (Cunningham et al., 2018; IPCC, 2023).

Conservation and Sustainable Utilization

The conservation of medicinal plants requires integrated approaches that combine in situ and ex situ conservation strategies. Protected areas, biosphere reserves, botanical gardens, seed banks, and tissue culture techniques play important roles in preserving threatened species and their genetic diversity (Chen et al., 2016; Fay, 2018). Sustainable harvesting practices and community-based resource management programs can also contribute to the long-term conservation of medicinal plant resources while supporting local livelihoods (Kala, 2015; Kunwar et al., 2021, Sikarwar 2026).

Medicinal plants constitute a vital component of global healthcare systems and provide primary health support for nearly 80% of the world's population. They also serve as an important source of raw materials for pharmaceutical, nutraceutical, and herbal industries. However, increasing commercial demand, habitat degradation, climate change, and unsustainable harvesting practices have led to a rapid decline in many medicinal plant species. Ensuring their long-term survival requires a balanced approach that integrates conservation with sustainable utilization while supporting biodiversity, local livelihoods, and traditional knowledge systems (Kunwar, et al 2021).

1. Conservation Strategies: In Situ and Ex Situ Approaches

The conservation of medicinal plants primarily relies on two complementary strategies: **in situ** and **ex situ** conservation.

In Situ Conservation

In situ conservation focuses on protecting plant species within their natural ecosystems. Protected areas such as biosphere reserves, national parks, wildlife sanctuaries, and sacred groves play a significant role in maintaining genetic diversity and ecological processes (Chen et al., 2016; Kala, 2023). In India,

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natural forests harbor the majority of medicinal plant species, yet many of these populations face severe threats due to excessive extraction and habitat destruction (Goraya et al., 2021; NMPB, 2024). The establishment of wild nurseries and community-managed conservation sites near natural habitats has emerged as an effective strategy for safeguarding rare, endemic, and threatened medicinal plants (Pandey & Tripathi, 2024; Hamilton, 2023).

Ex Situ Conservation

Ex situ conservation involves preserving plant species outside their natural habitats. Botanical gardens, medicinal plant conservation parks, seed banks, field gene banks, and tissue culture repositories help maintain valuable germplasm and reduce dependence on wild populations (Pandey & Tripathi, 2024; Chen et al., 2024). These facilities are particularly important for species that exhibit slow growth, poor natural regeneration, or high vulnerability to environmental disturbances (Pandey& Tripathi, (2024). Gupta et al., 2025). By cultivating threatened species under controlled conditions, ex situ conservation contributes to both biodiversity protection and sustainable raw material production (Ekiert et al., 2024; Sharma et al., 2024).

Role of Biotechnology

Modern biotechnological techniques have significantly enhanced conservation efforts. Methods such as tissue culture, micropropagation, synthetic seed production, cryopreservation, and molecular marker-assisted selection facilitate rapid multiplication of elite genotypes and production of disease-free planting material. These technologies not only support species recovery programs but also reduce harvesting pressure on wild populations by ensuring a continuous supply of planting stock. Atanasov et al 2021)

2. **Challenges to Conservation and Sustainable Utilization:** Medicinal plant resources face numerous threats that undermine their sustainability.

Over-exploitation and Habitat Loss

Commercial harvesting, agricultural expansion, urbanization, and deforestation continue to reduce natural populations of medicinal plants. Many high-value species are collected directly from the wild without adequate regeneration measures, leading to population decline and local extinction.

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Climate Change Impacts

Climate change has emerged as a major challenge for medicinal plant conservation. Rising temperatures, altered precipitation patterns, and increasing frequency of extreme weather events are affecting species distribution, growth, and phytochemical composition. Recent studies indicate that many medicinal plant species may experience habitat contraction, geographic range shifts, or increased extinction risk under future climate scenarios. High-altitude species such as *Nardostachys jatamansi* and *Paris polyphylla* are particularly vulnerable because of their narrow ecological requirements. Kardbhajne et al 2026, Pecl et al 2017)

Loss of Traditional Knowledge

Traditional medicinal knowledge, often transmitted orally across generations, is gradually disappearing due to modernization and cultural changes. In many regions, inadequate documentation of ethnobotanical practices limits the effective conservation and sustainable use of medicinal plants. Furthermore, destructive harvesting practices, especially root extraction, often result in the death of entire plants and contribute to population decline (Rout et al 2023

3. Sustainable Utilization and Management Practices

Sustainable utilization aims to meet present needs without compromising future availability of medicinal plant resources. (Selmar & Kleinwächter 2013).

Cultivation and Domestication

The cultivation of commercially important medicinal plants offers a practical alternative to wild harvesting. Organized cultivation reduces pressure on natural populations, improves quality control, and provides reliable income opportunities for farmers. Species with high market demand should be prioritized for domestication and large-scale cultivation. (Gautam et al 2023).

Good Agricultural and Collection Practices

Implementation of Good Agricultural and Collection Practices (GACP) ensures sustainable harvesting, traceability, and quality assurance. International certification systems such as FairWild promote responsible sourcing by balancing conservation objectives with economic benefits for local communities (Shukla 2023).

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Community-Based Conservation

Local communities possess extensive knowledge regarding medicinal plant identification, harvesting, and utilization. Their active involvement in conservation initiatives enhances long-term sustainability. Kardbhajne, & Dhadse, (2026). Participatory management approaches, community nurseries, benefit-sharing arrangements, and documentation of indigenous knowledge strengthen both biodiversity conservation and rural livelihoods. The principles of the Nagoya Protocol further support equitable sharing of benefits derived from biological resources. (WHO, 2019,2023), Schippmann et al 2023.

Policy Support

Government agencies and conservation organizations play a crucial role in promoting sustainable utilization through incentives, cultivation schemes, market development, and awareness programs. In India, initiatives supported by the National Medicinal Plants Board have encouraged conservation, cultivation, and value-chain development for medicinal plant species.

4. Integrating Science, Traditional Knowledge, and Policy

Effective conservation requires an interdisciplinary framework that combines ecological research, biotechnology, ethnobotany, and policy interventions.Advanced tools such as Geographic Information Systems (GIS), remote sensing, and species distribution models like Max Ent help identify priority conservation areas and predict future habitat suitability under climate change scenarios. These approaches assist policymakers in designing targeted conservation programs and climate adaptation strategies. (Jha, & Halder 2023, Kankam et al 2023)

Simultaneously, traditional ecological knowledge must be integrated into conservation planning. Indigenous communities often possess valuable insights into sustainable harvesting methods, species ecology, and ecosystem management. Combining scientific innovations with local knowledge can improve conservation outcomes while preserving cultural heritage. (Biswas et al 2023, Kulkarni & Deshmukh, 2025).

Sustainable Value Chains and Certification

Conservation efforts become more effective when linked with sustainable markets. Developing value-added products, establishing traceable supply chains, and promoting certification programs

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encourage responsible production and consumption. Certification schemes such as FairWild provide incentives for sustainable harvesting while ensuring economic returns to local stakeholders (Raghuvanshi, & Sharma 2025).

Conclusion

The long-term survival of medicinal plants depends on the successful integration of conservation and sustainable utilization strategies. In situ and ex situ conservation measures, supported by modern biotechnological tools, are essential for protecting threatened species and maintaining genetic diversity. At the same time, cultivation, sustainable harvesting practices, community participation, and effective policy frameworks can reduce pressure on wild populations. Given the increasing threats posed by climate change and the erosion of traditional knowledge, collaborative efforts among researchers, policymakers, local communities, and industry stakeholders are urgently needed. A holistic approach that combines scientific innovation with indigenous wisdom offers the most promising pathway for ensuring the continued availability of medicinal plant resources for future generations.

Climate change poses substantial challenges to medicinal plant diversity, distribution, and phytochemical composition, thereby affecting their ecological, medicinal, and economic value (IPCC, 2023; Sharma et al., 2020). Strengthening conservation efforts, promoting climate-resilient cultivation systems, and integrating traditional knowledge with modern scientific approaches are essential for ensuring the sustainable utilization of medicinal plant resources in the future (WHO, 2019; Chen et al., 2016).

Table 1. Major Climate Change Impacts on Medicinal Plants

Impact Category	Number of Species Affected	Percentage (%) of Studied Species	Consequences
Decline in suitable habitat	106	28.9	Reduced distribution and population size
Range shift/migration	94	25.6	Movement to higher altitudes or latitudes

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Increased habitat suitability	70	19.1	Potential expansion in limited regions
Risk of extinction	33	9.0	Possible loss of medicinal resources
Changes in bioactive compounds	24	6.5	Altered medicinal efficacy and quality
Habitat fragmentation	4	1.1	Reduced genetic diversity
Stable distribution	2	0.5	Minimal climate impact observed

Source: *Analysis of 367 medicinal plant species in a global scoping review Mykhailenko et al 2025, Takubessi et al. (2025)*

Table 2. Climate Factors and Their Effects on Medicinal Plants

Climate Factor	Effect on Plants	Examples of Impact
Rising temperature	Alters growth and phenology	Early flowering, reduced biomass
Drought stress	Reduces yield and survival	Lower root and leaf production
Elevated CO_2	Changes secondary metabolites	Altered alkaloid and phenolic content
Irregular rainfall	Habitat instability	Reduced regeneration rates
Extreme weather events	Population decline	Flood and heatwave damage
Altitudinal warming	Upward species migration	Loss of alpine medicinal species

***Source**: Climate–medicinal plant interaction studies Takubessi et al. (2025); Mansinhos et al. (2024); Laftouhi et al. (2023), IPCC. (2023), Newman, & Cragg 2020)*

Table 3. Highly Vulnerable Medicinal Plant Species Under Climate Change

Species	Medicinal Importance	Main Threat
Nardostachys jatamansi	Neuroprotective, sedative	Habitat contraction in Himalayas

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Paris polyphylla	Anticancer and anti-inflammatory	Climate sensitivity and overharvesting
Dendrobium nobile	Traditional medicine	Restricted distribution
Ephedra sinica	Respiratory disorders	Habitat degradation
Warburgia salutaris	Antimicrobial uses	Overexploitation and climate stress

***Source**: Global medicinal plant vulnerability assessments: National Medicinal Plants Board (NMPB). (2024). Annual Report 2023–24. New Delhi: Ministry of AYUSH, Government of India. Sharma et al 2020, Hamilton 2023, Sudhakaran (2024), Mykhailenko, et al. (2025).*

Table 4. Sustainable Adaptation Strategies for Medicinal Plants

Strategy	Objective	Expected Outcome
In situ conservation	Protect natural populations	Maintain genetic diversity
Ex situ conservation	Preserve germplasm outside habitats	Safeguard endangered species
Tissue culture & micropropagation	Mass multiplication	Reduce wild harvesting pressure
Climate-smart cultivation	Adapt production systems	Improve resilience and productivity
Species distribution modelling (MaxEnt)	Predict future habitats	Prioritize conservation areas
Community-based conservation	Engage local stakeholders	Sustainable resource management
FairWild certification	Promote responsible harvesting	Sustainable trade and livelihoods
Seed and gene banks	Long-term genetic preservation	Future restoration programs

***Source**: Recent sustainability and conservation literature: FairWild Foundation. , 2023Ansari, et al. (2023), Biswas, S., et al. (2023), Kankam, S., et al. (2023).*

Table 5. Future Sustainability Pathways for Medicinal Plant Conservation

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Pathway	Key Actions	Sustainability Benefits
Biotechnology-driven conservation	Cryopreservation, tissue culture, synthetic seeds	Rapid species recovery
Digital conservation planning	GIS, remote sensing, AI modelling	Improved decision-making
Cultivation expansion	Domestication of high-demand species	Reduced pressure on wild stocks
Traditional knowledge integration	Documentation and knowledge transfer	Cultural preservation
Climate-resilient value chains	Certification and traceability	Market sustainability
Policy and governance strengthening	Biodiversity laws and incentives	Long-term conservation success
International collaboration	CBD, Nagoya Protocol implementation	Equitable resource sharing

***Source**: Future Sustainability Pathways for Medicinal Plant Conservation Singh, A., et al. (2024), World Health Organization (WHO). (2023), Convention on Biological Diversity (CBD). (2022), International Union for Conservation of Nature (IUCN). (2024).*

Table 6. Key Statistics Highlighting the Urgency of Conservation

Indicator	Value
Medicinal plant species reviewed globally	367
Species classified as threatened	40.6%
Species not yet evaluated by IUCN	59.4%
Species projected to lose suitable habitat	106
Species expected to shift range	94
Species at risk of extinction	33
Wild-harvested medicinal plant sources	~71%
Threatened among wild-harvested species	~45%

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***Source**: Key Statistics Highlighting the Urgency of Conservation: International Union for Conservation of Nature (IUCN). (2024).* The IUCN Red List of Threatened Species. *Gland, Switzerland: IUCN. National Medicinal Plants Board (NMPB). (2024).* Annual Report 2023–24. *Ministry of AYUSH, Government of India, Takubessi et al. (2025)*

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