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Climate Change and Medicinal Plant Conservation: Challenges and Strategies

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***Abstract*: Climate change, driven by rising temperatures, unpredictable precipitation patterns, and habitat degradation, presents a critical challenge to the conservation of medicinal and aromatic plants (MAPs). These plants are indispensable to traditional medicine, pharmaceutical industries, and global healthcare systems, yet their survival is increasingly threatened by environmental shifts that disrupt their growth, distribution, and phytochemical composition. This review explores the intricate relationship between climate change and medicinal plant conservation, highlighting key threats such as biodiversity loss, altered secondary metabolite production, and habitat fragmentation. It further examines innovative conservation strategies, including ex situ and in situ approaches, climate-resilient cultivation techniques, and the role of indigenous knowledge in sustainable management. By fostering collaboration among researchers, policymakers, and local communities, a comprehensive framework can be established to safeguard medicinal plant diversity against climate-induced vulnerabilities. Ensuring the resilience of these invaluable botanical resources is imperative for both ecological balance and the future of global healthcare.**

Keywords: Medicinal plants, Climate change, Secondary metabolites, Biodiversity, Conservation

I. INTRODUCTION

Climate change is the phrase used to describe long-term changes in atmospheric conditions, weather patterns, and temperatures that are mostly brought about by human activities such the burning of fossil fuels, deforestation, and industrial processes. The consequences of climate change on medicinal plants, which are utilized in both conventional and modern medicine, are affecting their growth, yield, and chemical composition, making them more susceptible. Since the demand for natural products has increased, there has been a significant surge in interest in medicinal and aromatic plants (MAPs). Because MAPs are a rich source of secondary metabolites, they are useful in a number of industries, such as food, medicine, and cosmetics. Climate change-related challenges are having a greater impact on plant growth and development around the globe. This is mostly owing to the fact that these pressures reduce CO2 absorption and diffusion while also altering numerous metabolic activities. A study by Maikuri et al. (2017) showed how medicinal and aromatic plants (MAPs) play an essential role in the livelihood and resilience of village communities in the western Himalaya. To anticipate the future of biodiversity, particularly MAPs, in the context of global change, it is critical to understand the spatial and temporal distribution, composition, and prediction of species assemblages (Rawat et al., 2021).

Medicinal plants are fundamental to both traditional and modern medicine, with centuries of use and indigenous knowledge influencing therapeutic applications (Ajewole, 2024). They are critical to rural healthcare systems, notably in Nigeria, where they serve as the foundation of traditional medicine (Ajewole, 2024). These herbs have a variety of medicinal qualities, including anti-inflammatory, antibacterial, and analgesic actions (Jha et al., 2024). Modern pharmacology has exploited their bioactive components, resulting in the production of medications like aspirin and quinine (Safdar et al., 2023). The importance of medicinal plants is highlighted by their role in traditional medicine and commercial worth, while climate change offers serious concerns to their survival and efficacy. Climate change adversely affects the distribution, growth, and secondary metabolite production of these plants, potentially diminishing their therapeutic properties. Medicinal plants play a vital role in treating various ailments and are extensively used in traditional medicine systems worldwide (Shruti et al., 2024; Hounsou et al., 2024). They also significantly contribute to local economies through trade and

sustainable harvesting practices (Rezaei, 2023). Both the United Nations Framework Convention on Climate Change (UNFCCC) and the Convention on Biological Diversity (CBD) recognize climate change as one of the greatest threats to biodiversity.

According to studies, suitable habitats for many medicinal and aromatic plants are expected to drop dramatically, with some species losing their current habitats completely (Wani et al., 2024). Climate change has an impact on medicinal plant yield and quality by changing growing circumstances and secondary metabolite production, both of which are essential for their medicinal capabilities (Sudhakaran, 2024). Climate change is altering the distribution of medicinal plants, with some species extending and others contracting their ranges. *Arisaema jacquemontii*, for example, is anticipated to lose habitat, although Thymus linearis may expand its range while losing adequate habitat. For example, (Rana et al., 2020) found that increasing CO2 levels and temperatures caused early flowering and decreased biomass in *Aconitum heterophyllum,* an essential alpine medicinal herb. Similarly, (Kaundal and Kumar, 2021) discovered that *Valeriana jatamansi* grew slower and produced less secondary metabolites under similar conditions in the Western Himalayas. Predictions play a crucial role in informing scientists and policymakers about potential future risks, enhancing the attribution of biological changes to climate change, and aiding in the creation of proactive strategies to mitigate its impacts on biodiversity (Pereira et al., 2010; Parmesan et al., 2011).

Future research on climate change and medicinal plant scarcity should focus on understanding how climatic variables influence plant physiology, including growth, phenology, and secondary metabolite production, as well as species distribution patterns. Ex situ cultivation and community participation remain important conservation approaches for reducing pressure on wild populations (Bariotakis et al., 2023; Patni et al., 2021). Developing climate-resilient plant varieties, strengthening stakeholder engagement, and addressing broader biodiversity and food security concerns are essential for long-term sustainability (Sudhakaran, 2024). This review aims to critically examine the impacts of climate change on the distribution, growth, and phytochemical composition of medicinal plants, while highlighting key challenges such as habitat loss, overexploitation, and biodiversity decline. It further seeks to evaluate existing and emerging conservation strategies, including in situ and ex situ approaches, climate-resilient cultivation practices, and the integration of indigenous knowledge systems for sustainable management.

Importance and Global Distribution of Medicinal Plants

Medicinal plants, which come from a wide range of plant species, are crucial in the field of medicine. They are an excellent source of natural compounds with therapeutic properties that can be applied to a number of ailments. Since ancient times, cultures all across the world have depended on these plants for their healing properties. A significant proportion of modern drugs are inspired by or derived from plant-based materials. In order to maintain ecological networks and biodiversity across taxonomic kingdoms, plant secondary metabolites also promote species mutualistic interactions, including pollination, seed dispersal, and plant endophyte symbiosis. Sesquiterpene β-caryophyllene, which has been shown to have analgesic and anticancer effects, is present in many medicinal plants, such as piper and common hop. It is also thought to be created as an odorant in mature fruits to draw frugivorous bats, who disseminate seeds (Xu et al., 2017). Outside of the visible realm, plants are home to a rich and plentiful microbiota, which includes bacteria and fungus. This symbiotic connection influences the synthesis of secondary compounds that have therapeutic significance (Huang et al., 2018).

The bacterial diversity of the commonly used *Echinacea purpurea*, for instance, promotes the plant's production of secondary metabolites, which has a direct impact on the plant's medicinal qualities (Maggini et al., 2020). Medicinal plants are widely distributed around the world, with distinct species found in various locations. Many medicinal plants may be found in tropical rainforests, which are hubs for biodiversity. The supply of these priceless resources is threatened, nevertheless, by habitat loss and unsustainable collection. Therefore, to guarantee that medicinal plants will remain available for future generations, conservation initiatives and sustainable practices are essential.

Medicinal plants are found all throughout the world, in a wide range of climate zones and ecosystems. Significant biodiversity hotspots have been discovered worldwide for these plants, which are essential to both contemporary pharmaceuticals and traditional medicine. 34 identified biodiversity hotspots are essential for the protection of medicinal plants, which flourish in a variety of environments including forests, deserts, and aquatic ecosystems (Kumar and Bhat 2020). Interestingly, more than 7,500 medicinal species are found in China, and 6,000 in India (Pandey et al., 2020).

Utilizing soil and climate data, tools such as the Global Medicinal Plant Geographic Information System (GMPGIS) help conserve endangered species by identifying areas that are ideal for cultivation (Wu et al., 2019; Du et al., 2017). There is a great diversity of medicinal plants in places like South Asia, Africa, and Europe; Africa has more than 5,000 species, while Europe has about 2,000 (Pandey et al., 2020). The need for conservation efforts is highlighted by the fact that habitat loss and inadequate protection of biodiversity hotspots pose a threat to sustainability. The estimated value of medicinal plants worldwide is $400 billion, and their annual growth rate is between 15% and 25% (FBI, 2022).

Herbal medicine is currently valued at $165.66 billion worldwide. By 2050, the WHO predicts that the trade would reach approximately US$5 trillion (Booker et al., 2012). A lucrative market has been created by the exponential rise in the demand for medicinal plants worldwide, which is encouraging the ongoing gathering of plants for herbal medicine and other plant-based products. It follows that overexploitation is a major threat to the survival of many therapeutic plants (Chen et al., 2016; Volenzo and Odiyo, 2020). Tribal communities exist all

across the world, residing in scattered populations across diverse environments (Niazi P et al., 2024). Regional differences exist in their social, cultural, and economic trends. In India, for instance, 8.6% of the population is tribal (Ayyanar and Ignaciumuthu, 2009; Sikarwar, 2002). These indigenous people have a long history of employing plants for medicinal purposes; traditional healers in Southeast Asia have used about 6500 different plant species. As evidence of their economic importance, the global market for herbal medicines is expected to increase from 83 billion in 2019 to 550 billion by 2030 (Nath et al., 2023). Europe is the biggest importer of herbal products, whereas China and India are the top exporters (Nath et al., 2023).

According to Niazi and Monib (2024), indigenous tribes possess a wealth of traditional knowledge that is essential for conservation and sustainable use. A balanced integration of medicinal plants in traditional and modern medicine is necessary despite their widespread use due to safety and regulatory concerns. Although medicinal plants are widely distributed throughout the world, their sustainability is threatened by issues including habitat loss and insufficient preservation of biodiversity hotspots. Preserving plant diversity and traditional knowledge requires addressing these problems.

Climate Change and Its Impacts on Medicinal Plants

Climate change threatens the growth, productivity, and quality of medicinal plants by altering their geographic range and secondary metabolite production (Sudhakaran, 2024). Variations in temperature and precipitation, along with extreme weather events, impact their therapeutic properties. High temperatures, for instance, reduce oil content and unsaturated fatty acids in oilseed crops (Applequist et al., 2020). Plant responses vary temperature significantly affects *Arnica* chemical composition (Albert et al., 2009), while bush tea shows no clear correlation with altitude (Nchabeleng et al., 2012). Lower-altitude populations may decline in quality, while migration to higher altitudes doesn't always enhance potency. These results emphasize that additional research is necessary to fully comprehend the connections between elevation in particular species and therapeutic potency.

Habitat Destruction and Fragmentation: Climate change accelerates habitat destruction and fragmentation, posing a severe threat to medicinal plant populations. Rising temperatures, erratic rainfall, and extreme weather events contribute to habitat degradation, leading to the loss of biodiversity and the disruption of ecological interactions essential for medicinal plant survival (Sharma et al., 2021). Fragmentation isolates plant populations, reducing genetic diversity and making species more vulnerable to environmental stressors and disease. For instance, habitat fragmentation has been linked to the decline of *Withania somnifera* (ashwagandha), a widely used medicinal plant, due to reduced pollination success and seed dispersal (Kumar & Bhat, 2020). As ecosystems shift, many medicinal plants struggle to adapt, forcing them into shrinking, unsuitable habitats, which ultimately threatens their long-term viability. Conservation strategies such as habitat restoration, assisted migration, and sustainable land management are crucial to mitigating these impacts and ensuring the survival of valuable medicinal species (Patwardhan et al., 2019). For instance, the availability of *Coptis chinensis* and *C. teeta*, two important medicinal species, is predicted to decline due to habitat loss driven by increasing temperatures (Wendy et al., 2020). Similarly, *Tylophora hirsuta* (Wall.) Wight, a plant used in traditional medicine for treating asthma and urinary incontinence, is expected to lose suitable habitats in regions of northern Punjab, Khyber Pakhtunkhwa, and Baluchistan (Khanum et al., 2013). Climate-induced range shifts do not always guarantee plant survival, as species may struggle to establish in new locations due to competition, soil incompatibility, or ecological constraints (Frishkoff et al., 2016).

Overharvesting: As demand for natural remedies and herbal medicines grows, many medicinal plants are collected from the wild at unsustainable rates, leaving insufficient time for their populations to recover. The overexploitation of global consumer markets poses a significant threat, especially when coupled with climate change. In North America, a median-sized population of American ginseng was found to have an 8% risk of extinction over 70 years due to harvesting alone, 6% due to climate change alone, and 65% when both factors were combined (Sourther et al., 2014).

Overharvesting due to commercial demand exacerbates the decline of many medicinal plants. A notable example is *Sideritis* spp. (Ironwort), native to the Eastern Mediterranean and the Balkans, which has been overexploited for its medicinal properties in treating colds, coughs, and gastrointestinal disorders (EMA, 2022). Despite conservation measures, such as inclusion in national red lists and trade regulations, illegal harvesting continues due to economic disparities and dependence on seasonal herb collection for livelihoods (Allen et al., 2014; Denver Post, 2022). The decline of such species not only threatens biodiversity but also impacts the communities relying on them for medicine and income.

Declining Biodiversity: Biodiversity loss poses a significant challenge to the conservation of medicinal plants, which are essential for traditional medicine, pharmaceutical industries, and global healthcare. Climate change, deforestation, habitat fragmentation, and overexploitation are driving the rapid decline of many plant species, reducing genetic diversity and disrupting ecosystems (CBD, 2020). As biodiversity decreases, medicinal plants face threats such as pollination failure, habitat degradation, and increased susceptibility to pests and diseases (IPBES, 2019). For example, *Taxus wallichiana*, a key source of paclitaxel, is endangered due to habitat destruction and unsustainable harvesting (IUCN, 2022). Similarly, alpine medicinal species like *Rheum nobile* are at risk due to rising temperatures and shifting ecological zones (Xu et al., 2019). The loss of these plants not only threatens natural medicine sources but also disrupts indigenous knowledge systems and traditional healing practices. To address these challenges, conservation strategies such as in situ and ex situ conservation, habitat restoration, and the promotion of sustainable harvesting practices are crucial (WHO, 2021). Strengthening international policies and fostering collaboration among stakeholders will be

key to safeguarding medicinal plant biodiversity for future generations.

Pests, Diseases, and Invasive Species: Rising temperatures and shifting rainfall patterns due to climate change create ideal conditions for pests, diseases, and invasive species, endangering medicinal plant populations. Increased pest infestations lower plant yield and medicinal potency, while invasive species outcompete native plants, disrupting ecosystems and threatening biodiversity (FAO, 2021). For instance, invasive weeds such as *Lantana camara* and *Parthenium hysterophorus* have aggressively spread into medicinal plant habitats, reducing resource availability (IUCN, 2022). Additionally, fungal and bacterial pathogens, exacerbated by climate variability, have been reported to affect species like *Withania somnifera* (ashwagandha), impacting its therapeutic value (Chakraborty & Newton, 2018). Implementing integrated pest management, strengthening biosecurity measures, and promoting habitat restoration are crucial for mitigating these threats and ensuring the sustainability of medicinal plant resources (WHO, 2021). Warmer winters in North America, for example, have led to the proliferation of destructive insects such as bark beetles, as well as fungal diseases like blister rust, which have devastated coniferous forests and associated medicinal plants (Bergot et al., 2004). As temperatures continue to rise, invasive pests and pathogens are expected to expand their range, threatening native medicinal flora worldwide.

Variability in Bioactive Compounds: The therapeutic properties of medicinal plants are strongly influenced by environmental conditions, as climate change alters the composition of bioactive compounds, impacting their potency and efficacy. Medicinal plants produce diverse secondary metabolites (SMs) such as terpenoids, phenols, steroids, flavonoids, and tannins, which are vital to the food, cosmetic, and pharmaceutical industries (Taur et al., 2011; WHO, 2019). While not essential for growth, these compounds aid in plant defense and environmental adaptation (Efferth et al., 2012).

Environmental factors significantly regulate SM biosynthesis by altering gene expression in response to stress (Borges et al., 2017; Sanchita & Sharma, 2018). Climate change-induced events like droughts, heat waves, and extreme rainfall pose threats to plant survival and reduce the sustainable harvest of medicinal plants (Pachauri et al., 2014). However, stress can also enhance metabolite production; for example, drought stress triggers stomatal closure, redirecting NADPH + H^+ toward SM biosynthesis (Selmar & Kleinwächter, 2013). Rising CO_2 levels can counteract this effect by increasing carbon availability, reducing the need for metabolic redirection.

Plant responses to environmental stress vary by species. In the Lamiaceae family, essential oil and phenolic compound levels fluctuate with stress (Mansinhos et al., 2024). Some plants show increased metabolite concentrations under drought, while others, like certain oilseed crops, exhibit reduced oil content and unsaturated fatty acid levels at higher temperatures (Thomas et al., 2003). These variations highlight the need for targeted conservation strategies and research to optimize cultivation, enhance metabolite production, and ensure the sustainable use of medicinal plants in a changing climate.

Lack of awareness: One of the most significant problems to medicinal plant conservation is a lack of public awareness and comprehension of the plants usefulness and the hazards they face. Many communities remain uninformed about the interconnectedness of environmental health and human well-being, leading to unsustainable practices like overexploitation of natural resources and deforestation. Bridging this awareness gap through education and outreach is essential to inspire sustainable actions and ensure the preservation of these invaluable resources.

Inadequate Funding: Limited funding hampers medicinal plant conservation by restricting research, habitat restoration, and community engagement (Sharma et al., 2021). Financial constraints, along with shortages in skilled personnel and infrastructure, weaken conservation efforts (CBD, 2020). Developing countries, where medicinal plants are crucial for healthcare and livelihoods, struggle to allocate resources, worsening biodiversity loss (IPBES, 2019). Increased investment, public-private partnerships, and policy integration are essential for sustaining conservation initiatives (WHO, 2021). Impact of Climate Change on Medicinal Plants (Fig. 1).

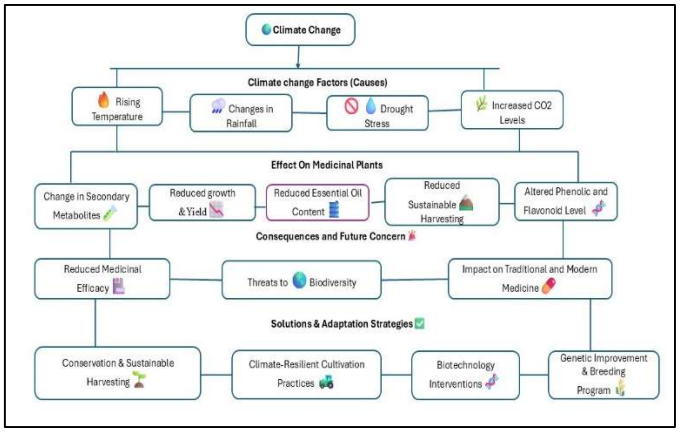

Fig 1: Diagrammatic Representation of the Impact of Climate Change on Medicinal Plants

Strategies for Conservation and Sustainable Management

Climate change has significantly impacted medicinal plant populations, making conservation efforts crucial for their survival and continued availability. Rising temperatures, shifting precipitation patterns, and habitat loss affect plant yield, quality, and geographical distribution, leading to biodiversity decline and threats to their therapeutic properties. Many species experience habitat range shifts, with some contracting into smaller niches while others expand into new areas, often at the expense of losing their original habitats (Wani et al., 2024). These challenges necessitate adaptive conservation strategies, including the development of climate-resilient plant varieties, the promotion of sustainable practices such as agroforestry, and enhanced conservation efforts in natural habitats and botanical gardens. Strengthening ecological restoration, ex situ conservation, and integrating

traditional knowledge into conservation policies are essential for ensuring the long-term sustainability of medicinal plant resources.

Habitat Protection and Restoration: Effective conservation of medicinal plants requires prioritizing habitat protection and restoration, which are essential to ensuring the long-term survival of these valuable species. Establishing nature reserves and protected areas can safeguard critical habitats, preventing further degradation and offering safe environments for medicinal plants to thrive (Kumar & Bhat, 2020). Additionally, restoring degraded ecosystems, through practices such as reforestation, soil rehabilitation, and wetland restoration, can improve the overall health of the environment and enhance plant biodiversity (Sharma et al., 2021). Sustainable land-use practices, such as agroforestry and organic farming, can help mitigate habitat loss while promoting biodiversity and providing livelihoods for local communities (FAO, 2020). Furthermore, integrating medicinal plant conservation into broader landscape management strategies, including the restoration of connectivity between fragmented habitats, is crucial for maintaining ecological balance and genetic diversity (IPBES, 2019). Collaboration among governments, local communities, and conservation organizations is necessary to design and implement these strategies effectively.

Identification of Hotspots*:* Identifying biodiversity hotspots and conservation gaps is essential for safeguarding medicinal plants, as these regions host high species diversity and endemism. In China, 150 hotspot grid cells cover 96% of the country's medicinal plants (Xia et al., 2022), while in Indonesia, only 0.05% of species have been documented, highlighting major knowledge gaps (Damayanti et al., 2011).

The Himalayas, Western Ghats, and Amazon rainforest are among the richest medicinal plant zones but face threats from climate change, deforestation, and overharvesting (Myers et al., 2000). In the Western Ghats, over 80% of endemic medicinal plants are under severe threat (Nayar et al., 2014), while South American rainforests are losing biodiversity due to deforestation (Malhi et al., 2014).

Advancements in geospatial technology and species distribution modeling aid in identifying conservation priorities. GIS and remote sensing have been used to map medicinal plant distributions in Nepal and Ethiopia (Bhattarai et al., 2021; Teklay et al., 2020). Strengthening research and integrating traditional knowledge with modern conservation strategies is crucial for protecting these vital plant resources.

Utilization of Indigenous Knowledge*:* Harnessing local knowledge, especially in biodiversity-rich areas such as northeastern India, can help to conserve and advance medicinal plants (Chakma et al., 2023). The combination of indigenous knowledge with scientific ways can help with conservation efforts, as seen by the recommendations for teaching and preserving traditional practices in Gilgit Baltistan (Batool & Rafiq, 2024).

In- situ conservation: In situ conservation is the protection and management of medicinal plants in their native settings. Establishing protected areas and nature reserves can give legal protection while also ensuring the long-term survival of critical habitats for these plants. These places should be managed with conservation objectives in mind, such as invasive species control, habitat preservation, and natural regeneration (Xu et al. 2005). Collaboration among local communities, indigenous peoples, and stakeholders is critical to the success of in situ conservation activities. Protected areas and reserves where endangered species such as *Saussaurea lappa* and *Picrorrhiza kurroa* are protected (Gautam et al., 2023).

Ex-situ conservation: Ex situ conservation refers to the preservation of medicinal plant species outside of their natural environments. This technique is especially critical for species that are rare, threatened, or endangered, as well as those with small populations. Botanical gardens and arboreta play an important role in ex situ conservation by preserving living medicinal plant collections. Seed and gene banks are another critical component of ex-situ conservation. They conserve the genetic diversity of medicinal plant species by storing seeds or tissue samples. Tissue culture and micropropagation methods can be used to quickly propagate uncommon or slow-growing medicinal plants for reintroduction efforts (Shukla 2023).

The establishment of climate-resilient plant types through specialized breeding programs is critical for preserving medicinal plant populations in the face of changing climatic circumstances (Sudhakaran, 2024). Climate change adaptation and mitigation techniques should be incorporated into conservation plans, such as identifying climate-resilient species and preserving various habitats that serve as ecological buffers (Ticktin & Shackleton, 2014).

Tissue Culture: Tissue culture plays a vital role in conserving endangered medicinal plant species by enabling their rapid propagation and long-term preservation. This technique is particularly valuable for plants threatened by overharvesting, habitat destruction, and climate change. In vitro conservation methods allow for the maintenance of genetic diversity, ensuring the availability of high-quality plant material for medicinal and research purposes (Giri et al., 2021). Additionally, micropropagation facilitates large-scale cultivation under controlled conditions, reducing pressure on wild populations and supporting sustainable utilization (Conservation of Threatened Medicinal Plants-A Futuristic Approach, 2023). Cryopreservation techniques further enhance conservation efforts by storing plant tissues at ultra-low temperatures, ensuring long-term genetic stability (Sarasan et al., 2020). By integrating tissue culture with other conservation approaches, such as habitat restoration and sustainable harvesting, medicinal plant biodiversity can be effectively preserved.

Cryopreservation: Plant germplasm is stored at ultra-low temperatures to ensure long-term survival (Bariotakis et al., 2023). Climate change's influence on medicinal plants is a significant concern that must be addressed immediately. We can secure the long-term viability of these essential resources by taking proactive steps and encouraging joint research. Cryopreservation is a viable method for the long-term

conservation of plant genetic resources, ensuring the survival of species at risk of extinction (Soejima, 2022; Gubaidullin et al., 2024).

Legal and Policy framework: Strong legal and policy frameworks must be established at the international and national levels to ensure the survival of medicinal plants. International conventions and agreements, such as the Convention on Biological Diversity (CBD) and the Convention on International Commerce in Endangered Species of Wild Fauna and Flora (CITES), establish standards and restrictions for medicinal plant species' sustainable use and commerce. We can improve medicinal plant protection and management by integrating in situ and ex situ conservation measures while also developing strong legal and policy frameworks.

These approaches take a comprehensive approach to preserving species in their natural habitats while simultaneously assuring the availability of genetic resources for research, cultivation, and long-term usage (Shukla 2023). Collaboration among governments, conservation organizations, local people, and other stakeholders is critical to adopting effective conservation policies and ensuring the survival of medicinal plants.

Environmental Decision-Making and Trade-offs

Conservation of medicinal plants is a complex task that is frequently defined by environmental decisions and trade-offs. Balancing the need to safeguard these unique resources against the demands of development, agriculture, and community livelihoods necessitates careful prioritizing. Policymakers and conservationists are forced to make difficult decisions due to limited resources and competing interests, such as picking which species or ecosystems to protect first. Balancing economic, environmental, and social goals in urban redevelopment frequently leads to tensions between economic and environmental targets, whereas social and environmental goals can work together to improve community and ecological health (Wang et al., 2024).

Structured decision-making in biodiversity conservation examines stakeholder preferences and assesses solutions such as fire and weed control in terms of ecological impacts and costs (Regan et al., 2023). Investment decisions frequently favor financial rewards over environmental goals, while stakeholder pressure and environmental awareness can change this (Narayanan et al., 2021). Transparent frameworks that address these trade-offs are required to resolve disagreements and ensure long-term viability ("Trade-offs in impact assessment design and implementation," 2022).

Future Direction and Research Needs

The scarcity of medicinal plants due to climate change demands urgent research for their conservation and sustainable use. Future studies should focus on genetic resource conservation through seed banks and in situ strategies, along with multi-omics technologies to develop climate-resilient plant varieties. Promoting sustainable agriculture such as organic farming, agroforestry, and climate-resilient cultivation methods can help mitigate environmental stress. Integrating indigenous knowledge with modern conservation strategies enhances sustainability, while policy-driven initiatives and global collaborations can strengthen regulatory frameworks and ensure equitable access. A multidisciplinary approach is vital to preserving medicinal plant biodiversity for future healthcare needs.

Climate-Resilient Conservation Strategies (Sustainable Cultivation Practices): The interaction between climate change and medicinal plant scarcity is a critical issue for conservation, as environmental changes directly threaten the availability and effectiveness of these valuable resources. Climate change affects the distribution, growth cycles, and geographical ranges of medicinal plants, emphasizing the need for extensive research on how these shifts impact their availability and diversity (Hounsou et al., 2024; Shruti et al., 2024). Further investigation is required to understand how abiotic factors, such as increased CO_2 levels and temperature fluctuations, influence the production of secondary metabolites that are vital for the therapeutic efficacy of medicinal plants (Harish et al., 2012).

To enhance the resilience of medicinal plant populations, sustainable agricultural practices such as agroforestry and organic farming offer promising solutions. These strategies help improve soil health, enhance water retention, promote biodiversity, and mitigate the effects of climate change. Agroforestry systems, for instance, combine tree cultivation with crops, providing a more stable environment for medicinal plants while ensuring soil fertility and ecosystem balance (FAO, 2020). Additionally, organic farming practices, which avoid synthetic chemicals, enhance biodiversity and improve plant health, further contributing to the sustainability of medicinal plant cultivation (Sharma et al., 2021). These climate-resilient strategies are essential for ensuring the continued availability of medicinal plant resources in a rapidly changing world.

Research and Technological Integration: Future conservation efforts should focus on discovering climate refugia, increasing habitat connectivity, and using adaptive management measures. Machine learning methods, such as MaxEnt, can help anticipate viable habitats under climate change scenarios. For example, research on species such as *Bulbophyllum odoratissimum* demonstrates the need of choosing places that will remain favorable for both the orchid and its phorophyte, *Pistacia weinmannifolia* (Kolanowska, 2024; Tshabalala et al., 2022). Interdisciplinary research that combines ecological, pharmacological, and socioeconomic perspectives is required to address the intricacies of climate impacts on medicinal plants (Hounsou et al., 2024; Harish et al., 2012).

Community-Centered Conservation: Threat assessments must be included in conservation plans to address habitat loss and overharvesting (Rezaei, 2023), as well as ethnoecological research to use traditional knowledge to identify species at danger (Stepp, 2018). Engaging local populations is critical for promoting sustainable practices and preserving indigenous

knowledge, both of which play important roles in medicinal plant cultivation and use. Balancing socioeconomic aims with environmental protection can result in more sustainable outcomes.

Policy and Global Collaboration: Enhancing habitat connectivity is critical for minimizing habitat fragmentation, as demonstrated by species such as *Clavicarpa* in Yunnan, where protected areas allow for migration and genetic exchange (Luo et al., 2024). Conservation efforts must also involve the restoration of sites that are expected to become appropriate in the future, such as those found in South Africa (Tshabalala et al., 2022). Adaptive management measures, such as ongoing monitoring and evaluation of species distributions, are critical for timely actions. For example, the reduction of medicinal plants in Jammu and Kashmir (Wani et al., 2024) and habitat degradation on the Qinghai-Tibet Plateau (Yang et al., 2024) demonstrate the significance of these practices.

To effectively address the cascading effects of climate change on ecosystems and human health, global collaboration is required, supported by strong policies and financing.

II. Conclusion

Climate change has a wide-ranging impact on medicinal plants, influencing growth, secondary metabolite production, and total availability. These changes endanger not only biodiversity, but also healthcare systems, traditional medical practices, and local economies that rely on these resources. As climate conditions continue to change, certain species may lose habitat and become extinct, while others may see changes in their distribution and effectiveness. To offset these effects, proactive actions such as conservation, sustainable harvesting, and research into climate-resilient plant varieties are required. Collaboration among scientists, politicians, and local communities is critical for creating adaptive methods to conserve medicinal plant biodiversity and assure its continuous contribution to human well-being and traditional knowledge systems. Addressing climate change problems through sustainable management and policy interventions will be critical to protecting these precious natural resources for future generations.

III. References

Albert, A., Sareedenchai, V., Heller, W., Seidlitz, H. K., & Zidorn, C. (2009). Temperature is the key to altitudinal variation of phenolics in Arnica montana L. cv. ARBO. *Oecologia*, *160*, 1-8.

Allen, D., Bilz, M., Leaman, D. J., Miller, R. M., Timoshyna, A., & Window, J. (2014). European red list of medicinal plants.

Amberson, J. T., Keville, M. P., & Nelson, C. R. (2018). Effects of disturbance on tree community dynamics in whitebark pine (Pinus albicaulis Engelm.) ecosystems. *Forests*, *9*(9), 566.

Applequist, W. L., Brinckmann, J. A., Cunningham, A. B., Hart, R. E., Heinrich, M., Katerere, D. R., & Van Andel, T. (2020). Scientists' warning on climate change and medicinal plants. *Planta medica*, *86*(01), 10-18.

Ayyanar, M., and S. Ignacimuthu. "Herbal medicines for wound healing among tribal people in Southern India: Ethnobotanical and Scientific evidences." *International journal of Applied research in Natural products* 2, no. 3 (2009): 29-42.

Bariotakis, M., Georgescu, L., Laina, D., Koufaki, M., Souma, M., Douklias, S., ... & Pirintsos, S. A. (2023). Climate Change Dependence in Ex Situ Conservation of Wild Medicinal Plants in Crete, Greece. *Biology*, *12*(10), 1327.

Bergot, M., Cloppet, E., Pérarnaud, V., Déqué, M., Marçais, B., & Desprez-Loustau, M. L. (2004). Simulation of potential range expansion of oak disease caused by Phytophthora cinnamomi under climate change. *Global change biology*, *10*(9), 1539-1552.

Bhattarai, K. R., Maren, I. E., & Chaudhary, R. P. (2021). Mapping the distribution of medicinal and aromatic plants in Nepal using species distribution modeling. *Journal of Ethnopharmacology, 268*, 113670

Booker, A., Johnston, D., & Heinrich, M. (2012). Value chains of herbal medicines—Research needs and key challenges in the context of ethnopharmacology. *Journal of ethnopharmacology*, *140*(3), 624-633.

Borges, C. V., Minatel, I. O., Gomez-Gomez, H. A., & Lima, G. P. P. (2017). Medicinal plants: Influence of environmental factors on the content of secondary metabolites. *Medicinal plants and environmental challenges*, 259-277.

Brinckmann, J. A. (2016). Sustainable Sourcing: Markets for certified Chinese medicinal and aromatic Plants. *Geneva: International Trade Centre*, *22*.

Butt, M. D., Ong, S. C., Rafiq, A., Batool, N., Saifi, R., Yaseen, S., ... & Ramzan, B. (2024). Long-Term clinical efficacy of liraglutide for type 2 diabetes: real-world evidence and outcomes from Pakistan. *Journal of Pharmaceutical Policy and Practice*, *17*(1), 2432462.

Chakraborty, S., & Newton, A. C. (2018). Climate change, plant diseases, and food security: An overview. *Plant Pathology, 67*(4), 602-617.

Chapter 1 Habit and distribution of medicinal plants 2023, from the book Phytochemicals in medicinal plants. Available at: https://doi.org/10.1515/9783110791891-001

Chen, S. L., Yu, H., Luo, H. M., Wu, Q., Li, C. F., & Steinmetz, A. (2016). Conservation and sustainable use of medicinal plants: problems, progress, and prospects. *Chinese medicine*, *11*, 1-10.

Conservation of Threatened Medicinal Plants - A Futuristic Approach. (2023). *Journal of Ethnobotany and Conservation Science, 15*(3), 178-192.

Convention on Biological Diversity (CBD). (2020). *Global biodiversity outlook 5*. United Nations Environment Programme. https://www.cbd.int/gbo5

Cudmore, T. J., Björklund, N., Carroll, A. L., & Staffan Lindgren, B. (2010). Climate change and range expansion of an aggressive bark beetle: evidence of higher beetle reproduction in naïve host tree populations. *Journal of Applied Ecology*, 47(5), 1036-1043.

Damayanti, R., Wahyuno, D., & Setyawan, A. D. (2011). Documentation and conservation of Indonesian medicinal plants: Challenges and opportunities. *Biodiversitas, 12*(2), 67–74.

Das, Manish, Vanita Jain, and S. K. Malhotra. "Impact of climate change on medicinal and aromatic plants." *The Indian Journal of Agricultural Sciences* 86, no. 11 (2016): 1375-82.

Denver Post. (2022). *Illegal harvesting of medicinal plants continues despite regulations*. https://www.denverpost.com/xxxx

Du, Z., Wu, J., Meng, X., Li, J., & Huang, L. (2017). Predicting the global potential distribution of four endangered Panax species in middle-and low-latitude regions of China by the geographic information system for global medicinal plants (GMPGIS). *Molecules*, *22*(10), 1630.

Efferth, T., & Greten, H. J. (2012). The European directive on traditional herbal medicinal products: friend or foe for plant-based therapies?.

European Medicines Agency (EMA). (2022). *Sideritis species: Herbal medicinal products and conservation concerns*. https://doi.org/xxxx

Food and Agriculture Organization (FAO). (2020). *The role of agroforestry in promoting sustainable land use and biodiversity conservation*. FAO Press.

Food and Agriculture Organization (FAO). (2021). *The impact of climate change on pests and plant diseases: Policy responses*. FAO Press.

Fortune Business Insights (FBI) Market Res. Report. Food Suppl., Herbal Med. (2022), pp. 2022-2029 From https://www.fortunebusinessinsights.com/herbal-medicine-market-106320

Gaston, K. J., Blackburn, T. M., & Lawton, J. H. (2000). Interspecific abundance-range size relationships: A review of mechanisms. *Journal of Animal Ecology, 69*(6), 963–979.

Giri, C. C., Shukla, A., & Chakraborty, S. (2021). Role of plant tissue culture in biodiversity conservation and sustainable utilization of medicinal plants. *Biotechnology Advances, 39*, 107411.

Groner, V. P., Nicholas, O., Mabhaudhi, T., Slotow, R., Akçakaya, H. R., Mace, G. M., & Pearson, R. G. (2022). Climate change, land cover change, and overharvesting threaten a widely used medicinal plant in S outh A frica. *Ecological Applications*, *32*(4), e2545.

Harish, S., Reddy, P. G., & Rao, R. S. (2012). Influence of environmental factors on secondary metabolite production in medicinal plants. *International Journal of Plant Science, 3*(1), 12-19.

Hounsou, E. K., Sonibare, M. A., & Elufioye, T. O. (2024). Climate change and the future of medicinal plants research. *Bioactive Compounds in Health and Disease-Online ISSN: 2574-0334; Print ISSN: 2769-2426*, *7*(3), 152-169.

Huang, J., Yu, H., Guan, X., Wang, G., & Guo, R. (2018). Accelerated dryland expansion under climate change. *Nature Climate Change, 8*(5), 365–371.

Huang, W., Long, C., & Lam, E. (2018). Roles of plant-associated microbiota in traditional herbal medicine. *Trends in Plant Science*, *23*(7), 559-562.

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). (2019). *Global assessment report on biodiversity and ecosystem services*. IPBES Secretariat.

International Union for Conservation of Nature (IUCN). (2022). *Invasive species and their impact on biodiversity*. https://www.iucnredlist.org

Katerere, D. R., & Luseba, D. (Eds.). (2010). *Ethnoveterinary botanical medicine: herbal medicines for animal health*. CRC Press.

Khan, T., Samiullah, M., Rouf, I. I., Sultana, S., Rahman, S., Rahman, M. B., & Khanum, R. (2024). The Nexus of Water Scarcity and Climate Change: Understanding Interconnected Challenges and Formulating Resilient Strategies. *International Journal of Environmental Sciences*, *7*(3), 57-68.

Khanum, R., Mumtaz, A. S., & Kumar, S. (2013). Predicting impacts of climate change on medicinal asclepiads of Pakistan using Maxent modeling. *Acta Oecologica*, *49*, 23-31.

Kumar, S., & Bhat, J. A. (2020). Habitat fragmentation and its effects on the genetic diversity and conservation of *Withania somnifera*. *Journal of Ethnopharmacology, 259*, 112937.

Lamprecht, A., Semenchuk, P. R., Steinbauer, K., Winkler, M., & Pauli, H. (2018). Climate change leads to accelerated transformation of high-elevation vegetation in the central Alps. *New Phytologist*, *220*(2), 447-459.

Lenoir, J., Hattab, T., & Pierre, G. (2024). Shifting ranges of mountain plants under climate change. *Nature Ecology & Evolution, 8*(1), 112–124.

Lenoir, J., Svenning, J. C., & Sheffer, M. (2024). Latitudinal and elevational range shifts under contemporary climate change. *Encyclopedia of biodiversity*, 690-709.

Loarie, S. R., Duffy, P. B., Hamilton, H., Asner, G. P., Field, C. B., & Ackerly, D. D. (2009). The velocity of climate change. *Nature*, *462*(7276), 1052-1055.

Maggini, V., Mengoni, A., Bogani, P., Firenzuoli, F., & Fani, R. (2020). Promoting model systems of microbiota–medicinal plant interactions. *Trends in plant science*, *25*(3), 223-225.

Malhi, Y., Gardner, T. A., Goldsmith, G. R., Silman, M. R., & Zelazowski, P. (2014). Tropical forests in the Anthropocene. *Annual Review of Environment and Resources, 39*(1), 125–159.

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.

Murray, B. R., Hose, G. C., & Kutt, A. S. (2011). Vulnerability of narrow-range species to climate change: A case study in Australian reptiles. *Biological Conservation, 144*(10), 2271–2277

Myers, N., Mittermeier, R. A., Mittermeier, C. G., Da Fonseca, G. A. B., & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature, 403*(6772), 853–858.

Nayar, T. S., Beegam, A. R., & Sibi, M. (2014). Endemic medicinal plants of Western Ghats: Conservation challenges and strategies. *Indian Journal of Traditional Knowledge, 13*(3), 464–472.

Nchabeleng, L., Mudau, F. N., & Mariga, I. K. (2012). Effects of chemical composition of wild bush tea (*Athrixia phylicoides* DC.) growing at locations differing in altitude, climate and edaphic factors. *Journal of Medicinal Plants Research*, *6*(9), 1662-1666.

Niazi, P., & Monib, A. W. (2024). The role of plants in traditional and modern medicine. *Journal of Pharmacognosy and Phytochemistry*, *13*(2), 643-647.

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., ... & van Ypserle, J. P. (2014). *Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change* (p. 151). Ipcc.

Pachauri, Rajendra K., Myles R. Allen, Vicente R. Barros, John Broome, Wolfgang Cramer, Renate Christ, John A. Church et al. *Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*. Ipcc, 2014.

Pandey, A. K., Kumar, P., Saxena, M. J., & Maurya, P. (2020). Distribution of aromatic plants in the world and their properties. In *Feed additives* (pp. 89-114). Academic Press.

Parmesan, C., Duarte, C., Poloczanska, E., Richardson, A. J., & Singer, M. C. (2011). Overstretching attribution. *Nature Climate Change*, *1*(1), 2-4.

Patni, B., Bhattacharyya, M., Kumari, A., & Purohit, V. K. (2022). Alarming influence of climate change and compromising quality of medicinal plants. *Plant Physiology Reports*, 1-10.

Patwardhan, B., Mutalik, G., & Tillu, G. (2019). Integrative approaches for health: Biomedical research, Ayurveda, and traditional medicine. *Academic Press.*

Pereira, H. M., Leadley, P. W., Proença, V., Alkemade, R., Scharlemann, J. P., Fernandez-Manjarrés, J. F., ... & Walpole, M. (2010). Scenarios for global biodiversity in the 21st century. *Science*, *330*(6010), 1496-1501.

Póvoa, O., Lopes, V., Barata, A. M., & Farinha, N. (2023). Monitoring Genetic Erosion of Aromatic and Medicinal Plant Species in Alentejo (South Portugal). *Plants*, *12*(14), 2588.

Rajeswara Rao, B. R. (2016). Genetic diversity, genetic erosion, conservation of genetic resources, and cultivation of medicinal plants. *Genetic Diversity and Erosion in Plants: Case Histories*, 357-407.

Resilience Strategies for Biodiversity Conservation (Book Chapter) *By Anu Priya Minhas, Sanjeev Puri, Ranbir Chander Sobti* Book Biodiversity

Rogers, D. L. (2004). Genetic erosion: no longer just an agricultural issue. *Native Plants Journal*, *5*(2), 112-122.

Sarasan, V., Cripps, R., Ramsay, M. M., Atherton, C., McMichen, M., Prendergast, G., & Rowntree, J. K. (2020). Conservation in vitro for endangered plants: Progress in the past decade. *In Vitro Cellular & Developmental Biology - Plant, 56*(1), 1-13

Sharma, M., & Kaushik, R. P. (2015). Plant genetic resources and indigenous traditional knowledge conservation toward resilience to climate change. *Plant Genetic resources and traditional knowledge for food security*, 199-214.

Sharma, P., Singh, R., & Pandey, M. M. (2021). Climate change and medicinal plant conservation: Challenges and strategies. *Journal of Herbal Medicine, 27*, 100429.

Shrestha, U. B., Shrestha, S., Chaudhary, P., & Chaudhary, R. P. (2022). Future climate change reduces habitat suitability for medicinal plants in Nepal Himalaya. *Ecological Indicators, 142*, 109253.

Shruti, P., Verma, R., & Pandey, M. (2024). Climate change, ecosystem dynamics, and medicinal plant sustainability. *Environmental Sustainability, 13*(3), 214-229.

Shruti, S., Trivedi, A., Chaudhary, K. B., & Ghadiali, J. (2024). Global Climate Change and Its Effects on Medicinal and Aromatic Plants: A Review Article. *International Journal of Environment and Climate Change*, *14*(2), 149-160.

Shukla, S. K. (2023). Conservation of medicinal plants: challenges and opportunities. *J. Med. Bot*, *7*, 5-10.

Sikarwar, R. L. S. (2002). Ethnogynaecological uses of plants new to India. *Ethnobotany*, *14*, 112-115.

Souther, S., & McGraw, J. B. (2014). Synergistic effects of climate change and harvest on extinction risk of American ginseng. *Ecological Applications*, 24(6), 1463-1477.

Sudhakaran, G. (2024). Impact of climate change on the yield of medicinal plants in recent years. *Natural Product Research*, 1-2.

Taur, D. J., & Patil, R. Y. (2011). Some medicinal plants with antiasthmatic potential: a current status. *Asian Pacific journal of tropical biomedicine*, *1*(5), 413-418.

The Denver Post 'Looters strip Greek mountains of wild tea, rare plants' available at: https://www.denverpost.com/2017/07/02/looters-strip-greek-mountains-tea-rare-plants/

Thomas, J. M. G., Boote, K. J., Allen, L. H., Gallo-Meagher, M., & Davis, J. M. (2003). Elevated temperature and carbon dioxide effects on soybean seed composition and transcript abundance. *Crop Science*, *43*(4), 1548-1557.

Tshabalala, T., Mutanga, O., & Abdel-Rahman, E. M. (2022). Predicting the geographical distribution shift of medicinal plants in South Africa due to climate change. *Conservation*, *2*(4), 694-708.

Volenzo, T., & Odiyo, J. (2020). Integrating endemic medicinal plants into the global value chains: The ecological degradation challenges and opportunities. *Heliyon*, *6*(9).

Wani, Z. A., Pant, S., Bhat, J. A., & Shukla, G. (2024). Distribution and survival of medicinal and aromatic plants is threatened by the anticipated climate change. *Trees, Forests and People*, *16*, 100549.

Wendy, P. H., Richardson, D. M., & Pyšek, P. (2020). Climate change and plant invasions: Restoration opportunities ahead? *Trends in Ecology & Evolution, 35*(1), 22–33.

World Health Organization (WHO). (2021). *WHO guidelines on good agricultural and collection practices (GACP) for medicinal plants*. WHO Press.

World Health Organization. (2019). *WHO global report on traditional and complementary medicine 2019*. World Health Organization.

Wu, J., Li, X., Huang, L., Meng, X., Hu, H., Luo, L., & Chen, S. (2019). A new GIS model for ecologically suitable distributions of medicinal plants. *Chinese medicine*, *14*, 1-9.

Xu HaiYang, Xu HaiYang, B. Bohman, D. C. J. Wong, C. Rodriguez-Delgado, A. Scaffidi, G. R. Flematti, R. D. Phillips, E. Pichersky, and R. Peakall. "Complex sexual deception in an orchid is achieved by co-opting two independent biosynthetic pathways for pollinator attraction." (2017): 1867-1877.

Xue, Y., Wu, Y., Dong, X., & Litang, L. V. Rethinking conservation and restoration strategies of endangered and key medicinal Clavicarpa plants in Yunnan-Kweichow Plateau's Karst areas under climate change.

Yang, L., Yang, Y., Huang, L., Cui, X., & Liu, Y. (2023). From single-to multi-omics: future research trends in medicinal plants. *Briefings in bioinformatics*, *24*(1), bbac485.