ĀRYAVAIDYAN, Vol. 37, No. 4, May - July 2024, Pages 71 - 81

The Silent Epidemic: Biodiversity Decline and its threat to Medicinal Plants

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Received: 20.05.2024 Revised: 02.07.2024 Accepted: 30.07.2024

ABSTRACT: India known for its diverse landscapes and rich biodiversity, is the home to approximately 45,000 plant species with around 15,000 having medicinal importance.[1] This biodiversity has been integral to the ancient Indian healing system of *ayurveda,* which utilizes plant-based formulations for wellness and disease management. The global reliance on traditional medicines, including *ayurveda* highlights the significant role of medicinal plants in healthcare. However, global climate change poses a serious threat to the region's biodiversity of medicinal plants. Factors like decreased rainfall, rising temperature, elevated CO_2 levels and changes in soil properties have significantly altered plant diversity.[2] Consequently, many drugs derived from these plants, crucial in ayurvedic practice are affected.[3] Both developing and developed nations are increasingly exploring forest-based medicinal plant products due to demand for pharmaceuticals and medicinal herbs, driven by growing health awareness.[4] Several Indian states have established Medicinal Plant Boards to conserve medicinal plants. Climate change has caused shifts in flowering plant and insect pollinator phenology, threatening both populations and impacting plant-pollinator systems.[5] India's diverse climatic zones may cause variations in plant species phytochemical composition. This review article discusses the role of medicinal plants in traditional practice, status of medicinal plants in trade and pharmaceutical industries, causes of biodiversity loss, climate change and its impact on medicinal plants and its phytochemicals.

Key Words: Biodiversity, Ayurveda medicinal plants, endangered plants, Phytoconstituents

INTRODUCTION

Medicinal plants have long been integral to healthcare in developing nations, with the majority of the population relying on traditional healing systems like *ayurveda* and traditional Chinese medicine. However, the advent of modern technologies has transformed these plants into sought-after commodities, sparking a patent race among countries to mine them for valuable phytochemicals.[6] Many drugs, from treating constipation to cancer; are derived from plants, with a significant portion of prescription drugs in the USA containing plant-based ingredients.[6] The value of these drugs is substantial, reaching billions of dollars. India ranks among the world's top 12 countries known for their extensive biodiversity, encompassing 10 distinct biogeographic regions. Within India, two of the world's eight biodiversity hotspots are situated. The country's diverse climatic conditions, varying altitudes and a range of ecological habitats have fostered the growth of exceptionally rich vegetation, particularly in medicinal plants. These plants serve as crucial sources of raw materials for traditional medical systems and pharmaceutical industries both domestically and internationally. The World Health Organization recognizes over 21,000 plant species globally for medicinal use. However, available data indicates that only 1,800 species are utilized in classical Indian systems of medicine, with Ayurveda employing 1,200, Siddha 900, Unani 700, Amchi 600, and Tibetan 450 species.[7] The distribution of traded species is also noteworthy, spanning various biogeographic zones, habitats and landscapes. Approximately 18% of these species are confined to the Himalayan and Trans-Himalayan regions, including North East India, while around 4% are restricted to the Western

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Ghats and 0.5% is exclusive to the Desert zone. The majority, roughly 77%, have a broader distribution across other biogeographic zones within the country.

In India, there exist roughly 8,000 medicinal plant species utilized by diverse communities across various ecosystems. However, only approximately 10% of these, totalling 880 species, are actively involved in trade. Among these traded species, around 48 are exported as raw drugs and extracts, while about 42 are imported. Regrettably, the wild populations of approximately 100 traded species have seen a decline, rendering them threatened. This highlights the current scenario of raw drug trade in India. Before delving into the reasons behind this trend, it's important to examine the specifics of what raw drugs are traded, where they come from, and their quantities. The analysis of the 880 medicinal plants reveals a diverse distribution across various life forms, with the majority categorized as herbaceous plants. Herbs, including grasses, represent the largest proportion at 41%, followed by trees at 26%, shrubs at 17%, and climbers at 16%. Additionally, these traded plants are spread across 151 families, with 79% classified as dicots, 11% as monocots, 5% as pteridophytes and 3% as gymnosperms. Fungi and lichens each comprise only 1%. [7] This distribution indicates that a very small fraction of raw drugs originates from lower classes within the plant kingdom.

Traditional medicine

Traditional medicine, often labelled as complementary or alternative medicine, has a rich history of harnessing the healing properties of the Earth's natural systems, including medicinal plants, animals, clean air, spring water and natural landscapes. These elements are fundamental to traditional healing practices worldwide. Systems like Chinese, Ayurveda, Unani and folk medicine make use of a wide range of natural materials for medicinal purposes, crafting thousands of remedies from leaves, herbs, roots, bark, animal products, minerals and other natural substances. The diversity of these remedies reflects the abundant biodiversity of the ecosystems, they originate from. Traditional medicine relies heavily on the biotic environment, drawing health benefits from intact ecosystems, genetic diversity, clean water and climate regulation provided by nature's services. Preserving biodiversity is therefore crucial for sustaining traditional healing practices and promoting community health and well-being. In many parts of the world, traditional medicine serves as a primary form of healthcare, especially where modern medical resources are scarce. Recognizing the significance of traditional medicine emphasizes the importance of safeguarding biodiversity and natural resources to ensure sustainable health outcomes. Effective management of social, economic and environmental resources is essential for safeguarding population health over time. The need for holistic approaches to health and well-being is underscored by contemporary public health challenges, which often arise from socio-economic disparities and unsustainable consumption patterns. Understanding the connections between traditional medicine and biodiversity is crucial for appreciating the interdependence of human health, cultural traditions and the natural environment. [7] Valuing and preserving biodiversity support both traditional healing practices and sustainable health outcomes for future generations.

Endangered medicinal plants[7]

The burgeoning herbal products industry presents a significant opportunity for economic development in India. The utilization of herbs for food, medicine, fragrance, flavour, dyes and various other purposes within Indian traditional medicine systems is on the rise. Presently, an estimated 95% of the medicinal plants utilized in the Indian herbal industry are harvested from the wild. Unfortunately, around half a million tonnes of dry material are collected annually through destructive means, leading to indiscriminate clearing of approximately 1.65 lakh hectares of forest each year. With population growth, rapid expansion of

agricultural and commercial land, deforestation, urban sprawl and industrialization encroaching upon rural areas, there is a notable depletion of India's plant genetic resources, with many species inching closer to extinction. Alarmingly, 427 Indian medicinal plant species are listed in the red data book as endangered, with 28 considered extinct, 124 endangered, 81 rare and 34 insufficiently known. It is imperative to promote the propagation and cultivation of these plants to mitigate their decline. Collection of certain species from the wild should be banned to prevent further harm. Plants are *Aconitum sp*. (Monk's Hood, *Vatsanaabhi)*, *Acorus* sp.(Sweet Flag, *Vacaa*), *Anchusa strigosa* (Gaozaban), *Aristolochia bracteata* (*Kiramar*, *Keetamaari*), *Artemisia annua* (Worm wood, *Damanaka*), *Atropa acuminata* (Indian belladonna, *Hṛtpatri*), *Berberis aristata* (Indian Berbery, *Daaruharidra*), *Brunium persicum* (Kala Zeera), *Chlorophytum sp*. (Safed Musli, *Musali*), *Colchicum luteum* (Tara-Tutiya, *Suraanjana*), *Commiophora wightii* (*Guggulu)*, *Coscinium fenestatum* (*Daruharidra*), *Coptis teeta* (Gold Thread, *Mamira (Peetarohiṇi*), *Curculigo orchioides* (*Kṛshna Musali*), *Didymocarpus pedicellata* (*Śilaa Pushpa*), *Drosera sp*. (Sundew), *Ephedra gerardiana* (*Somalata*), *Eulophia campestris* (*Saleb Misri*), *Ferula jaeschkeana* (Indian Hing, *Hingu*), *Gentiana kurroa* (Indian Gentian, *Trayamaaṇa)*, *Gloriosa superba* (Glory Lily, *Laangali)*, *Gynocardia odorata* (Kadu Bonsha), *Holostemma annualare* (*Jeevantee*), *Hydnocarpus sp*.(*Tuvaraka*), *Hyoscyamus niger* (Henbane, *Parasikayavaani*), *Inula racemosa* (*Pushkar Mool*, *Pushkaramoola)*, *Iphigenia indica* (*Nirpani*), *Lilium polyphyllum* (*Ksheera Kaakoli*), *Microstylis nicifera* (*Jeevaka*), *Microstylis wallichii* (*Ṛshabhaka*), *Nardostachys grandiflora* (*Jaṭamaansi*), *Onosma bracteatum* (Ratnajyot, *Gojihwa*), *Orchis latifolia* (*Saalamisri*), *Panax pseudo-ginseng var. himalicus (*Indian Ginseng), *Physochlaina praealta* (Scholar, Lalthang), *Picrorhiza kurroa* (Kutki, *Kaṭukurohiṇi*), *Piper cubeba* (*Kababchini, Kankola*), *Podophyllum hexandrum (*Bankari*, Giriparpata), Rauvolfia serpentina (Sarpagandha), Rheum astrata (Rewadchini), Rheum emodi (*Indian Rhubarb*, Gandhini), Saussurea sp (kushṭha), Swertia chirayata (Chirayata, Kiraatatiktaa), Taxus baccata (Taleespatra), Taxus wallichiana* (Indian Yew)

LOSS OF BIODIVERSITY OF MEDICINAL PLANTS

Environmental factors[7]

Rainfall: Over recent years, there has been a decrease in annual rainfall, leading to adverse effects on the health of numerous herbaceous species, particularly during the summer months.

Deforestation: Reports indicate a significant increase in deforestation activities over the past two decades. Factors such as agricultural expansion, logging, firewood collection, heavy grazing and other human activities have contributed to the reduction in valuable forest areas. As a consequence, many valuable wild medicinal plant species are either eradicated or significantly diminished each year.

Siltation of water bodies: The siltation of water bodies within forested areas has led to a decrease in their water-holding capacity, resulting in the depletion of underground water sources.

Lack of pollinators: There has been a notable decline in honey bee populations by as much as 50-60% in forests and other habitats. This decline in pollinator populations has resulted in reduced seed production and dispersal, impacting the ecosystem's reproductive processes.

Developmental activities[7]

Submersion: The forests, such as Maradavally, situated in the catchment area of Linganamakki Dam in Karnataka, are experiencing loss of numerous medicinal plant species due to submersion. Approximately 10 square kilometers of forest area is submerged during the monsoon season, leading to the disappearance of valuable medicinal plants.

Infrastructure: The expansion of roads, installation of power lines and construction of buildings have resulted in significant damage to forests and medicinal plants. For instance, the Devanarayandurga forest in Karnataka has been adversely affected by such infrastructure development.

Agriculture and forestry methods

Monoculture: There has been a continuous rise in the establishment of monoculture plantations comprising both economically significant native and non-native species within forests. Monoculture planting significantly impacts natural productivity, leading to decreased ecological stability and complexity, resulting in the depletion of medicinal plants. For example, the proliferation of Eucalyptus and Acacia species in various forest areas has contributed to this phenomenon.

Encroachments: Incursions into forest lands have reached concerning levels. Besides the felling of trees and clearance of vegetation, agricultural activities carried out on steep slopes have triggered soil erosion and a decline in medicinal plant diversity.

Over-exploitation: The collection of medicinal plants from forests has been widespread. Initially conducted by unregulated forest collectors who sold their harvest to contractors at predetermined prices, the practice has seen some regulation due to the efforts of the 'Local Traditional Medicinal Practitioners Association'. Awareness campaigns led by this association have helped curb illegal gathering to some extent.

STATUS OF MEDICINAL PLANTS IN INDIA

In the contemporary Indian economy, medicinal herbs hold significant importance, with approximately 70% of India's forest product exports attributed to Non timber forest products (NTFPs). The demand for phytochemicals is anticipated to become a burgeoning trade frontier in the foreseeable future. India boasts a rich cultural heritage in the utilization of medicinal herbs, but unfortunately, a large portion of traded herbal materials still originate from wild habitats, with only a few species cultivated to meet demand. This increasing trade poses severe threats to numerous plant species, many of which are endangered or at risk of extinction due to rapid loss of natural ecosystems and over exploitation.[7] To address the escalating demands of the Indian herbal industries, which are projected to generate an annual turnover of US$ 300 million, medicinal herbs are harvested from nearly 165,000 hectares of forests in India annually.[8] However, this exploitation, coupled with the pressures from a growing human population, poses risks to India's natural forests, leading to a decline in species diversity, primarily due to illegal harvesting and deforestation.

Several species of medicinal herbs in India, such as *Saussurea lappa* is considered under threatened category over the years. Additional species like *Berberis aristata* and *Picrorrhiza kurroa* face similar challenges.[9] Recognizing the urgency of the situation, the Indian Subcontinent Plant Specialist Group identified several species for detailed study and protection. Moreover, the establishment of Medicinal Plant Conservation Areas (MPCAs) by state forest departments in collaboration with international organizations aims to preserve germplasms for genuine, high-quality planting materials and conduct recovery research on threatened species.[10] Medicinal Plant Boards set up by various states in India focus on enhancing the status of medicinal plants through conservation practices, both *ex situ* and *in situ*. These initiatives play a crucial role in capacity building for forestry personnel, local communities and researchers, ensuring the sustainable use and equitable benefit sharing of India's medicinal plant resources. [11]

Market Demand and Supply of Medicinal Plants

The National Medicinal Plants Board (NMPB), in collaboration with the Indian Council of Forestry Research and Education, Dehradun (ICFRE), conducted extensive market surveys of medicinal herbs in India to evaluate the demand and supply

dynamics. In the fiscal year 2014-15, the combined commercial demand for raw plant-based drugs was estimated at 512,000 metric tons (MT). Conversely, exports of plant-based raw drugs and herbal extracts were estimated at 134,500 MT during the same period. The domestic market consumption by herbal industries was estimated at 195,000 MT, with approximately 167,500 MT of plant-based raw drugs consumed annually by rural households. The survey identified around 1,178 medicinal herbs involved in trading practices, with roughly 242 plant species being utilized annually in quantities exceeding 100 MT. [12]

Significance in modern drug industries on commercial basis

NMPB has devised comprehensive strategies to foster the conservation, cultivation, research, processing and marketing of herbal raw materials, aiming at the advancement of this sector. Various export promotion councils such as Pharmaceutical Export Promotion Council (PHAREXCI), Shellac and Forest Products Export Promotion Council (SHEFEXCIL), and Chemicals, Pharmaceuticals and Cosmetics Export Promotion Council (CHEMEXCIL) oversee the export of pharmaceuticals, forest products and chemical substances, respectively. Biotechnological methods have proven effective in enhancing the yield and phytoconstituent contents of medicinal plants. [13] For instance, *Chlorophytum borivilianum* (Safed Musali), known for its aphrodisiac properties, shows increased root production through controlled sucrose concentrations and CO_2 levels.[14] Similarly, conventional breeding improved seed yield and L-Dopa content in *Mucuna pruriens*[15], yielding a stable line named "Zandu Kauncha."

Preservation of plant diversity is crucial in safeguarding Ayurveda. An audit of industry's annual consumption of raw material is essential. Cultivation should be done in such a level that it supplements the procurement. Otherwise the situation will prompt the manufacturers, resorting to adulteration and substitution. There are also chances for adding low quality raw materials in the formulations. Rare status of a medicinal plant can make it expensive which is reflected in the price of the prepared medicine. The drug industry in an effort to thrive may move to unethical practices in marketing also.

CLIMATE CHANGE PROBLEMS AND THEIR AGENTS

Climate change poses a grave concern, with rising temperatures and melting glaciers posing significant threats to humanity. Its impact extends to water resources, food security and health, altering weather patterns including temperature, humidity, wind and the hydrological cycle. Globally, temperatures have surged by 0.85°C over the past three decades, with projections indicating a potential rise of 1.4-5.8°C during the 21st century[16], largely attributed to the escalating atmospheric CO_2 concentration, increasing by 20 ppm per decade.[17]. Anticipated effects include more severe heat waves, frequent wildfires, prolonged droughts, unpredictable storms and rising sea levels.

Farmers are particularly vulnerable to these weather extremes, which affect various crops, including cereals, horticultural plants, spices, ornamentals, and medicinal herbs.[18] Fluctuating climate conditions limit access to water, light, and nutrients, impairing vital plant processes like photosynthesis, respiration, biomass accumulation and pollination[19,20]. While initial stages may see a boost in photosynthesis, prolonged nutrient scarcity leads to its decline. The changing climate also threatens plant species populations and biodiversity distribution[21], impacting production and altering the biochemical properties and quality components of medicinal crops, thus diminishing profits.[20]

Adverse climate conditions further disrupt farm operations, affecting soil texture, inviting insect infestations, and reducing fertilizer, nutrient and water use efficiency.[19] Increased atmospheric CO_2 levels influence plant-microbe interactions, potentially affecting nitrogen fixation and green house gas emissions, thereby altering aerosol production, cloud properties, and radiative forcing. Combustion processes release CO_2 and N_2O,

while methane emissions primarily stem from livestock and rice cultivation. Nitrogenous fertilizers exacerbate nitrous oxide emissions, contributing to atmospheric pollution.[22]

To mitigate these impacts and maintain Earth's climate sustainability, efforts must focus on conserving natural resources, promoting afforestation, cultivating climate-resilient crops, implementing greenhouse plantation practices, and adopting modern irrigation technologies.[23,24] These measures are crucial for safeguarding the environment and ensuring a sustainable future amidst climate change challenges.

Climate change and biodiversity

Climate change is poised to have profound repercussions on biodiversity. Projections indicate that by 2100, the current temperature rise of 1.4°C could escalate to as high as 5.8°C. Already, biodiversity is feeling the effects of climate change, as species grapple with unstable habitats, altered life cycles and the emergence of new physical traits. Species capable of rapidly expanding their ranges or tolerating diverse climatic conditions may thrive in this rapidly changing environment traits shared by many invasive plant species. At the genetic level, climate change threatens biodiversity by diminishing the genetic diversity of populations through directional selection and abrupt migration, potentially disrupting ecosystem functioning and resilience.[25] Climate-induced phenological shifts in flowering species and their insect pollinators can create mismatches, leading to the extinction of both plant and pollinator populations, with far-reaching implications for plant-pollinator systems.[25,26] On a broader scale, climate change can induce significant fluctuations in vegetation communities, potentially disrupting biome integrity. Shifts in vegetation types may lead to forest degradation and biodiversity loss, especially at transition zones between forest types. For instance, rising temperatures at higher altitudes could trigger transitions from lower altitude temperate and sub-temperate forests to higher altitude alpine and sub-alpine forests, resulting in the extinction of several temperate flora types.[27]

Impact of climate change on the diversity of medicinal plants

Climate change poses a significant challenge to the survival of medicinal plants worldwide. It is characterized by shifts in seasonal patterns, weather conditions, temperature ranges and other related phenomena on a global scale. The Western Ghats, renowned for its rich biodiversity in India, is particularly vulnerable to the impacts of climate change.[28] For instance, *Garcinia indica* (*amlavetasa*) a valuable indigenous medicinal plant found in Maharashtra and Goa within the Western Ghats, is facing threats to its habitat. Efforts are underway to rehabilitate and reintroduce this species to mitigate the impacts of climate change.[30] Studies suggest that key bioclimatic factors like temperature seasonality, isothermality, annual precipitation and precipitation seasonality are expected to undergo significant changes. This could lead to a reduction in suitable habitats for medicinal plants by 2050, with further declines projected by 2070.[30] The Western Ghats, known as the origin of *Piper nigrum (maricam)*, a valuable crop with various medicinal properties, faces challenges due to projected climate scenarios and reduction in the habitat of *P. nigrum* in the Southern Western Ghats, home to several wild cultivars of this species.[29]

India boasts a diverse range of climatic zones, spanning from tropical regions in the south to temperate and alpine climates in the Himalayan north, with high-altitude areas receiving consistent snowfall during winter. Such vast climatic variations likely contribute to differences in the phytochemical composition of plant species. *Aloe vera (kumaari)*, recognized for its abundance of secondary metabolites with diverse medicinal properties, was studied across six agro-climatic zones in India. Analysis revealed variations in the presence and quantity of bioactive compounds such as glycosides, alkaloids, phenolic compounds and flavonoids among samples collected from

different zones, with highland accessions showing maximum antioxidant potential.[30] The Himalayan region of India is renowned for its rich biodiversity of medicinal plants, crucial for traditional healthcare and trade. However, high-altitude medicinal plant species are facing challenges due to excessive exploitation and climate change. Species like *Aconitum, Taxus, Ephedra*, and *Picrorrhiza,* among others, have significant market potential but are increasingly restricted to remote or protected environments.[31] Changes in phenology and distribution of medicinal plants in the alpine ecosystem of the Indian Himalayas are linked to temperature variability and alterations in snow patterns, highlighting the vulnerability of these species to climate change.[32]

Implications of climate change on secondary metabolites of plants

Changes in climate can impact both the production of secondary metabolites in plants and their overall growth, as alterations in metabolic pathways influence physiological functions, signalling mechanisms and defence responses. The rise in

Table 1
Effects of Climate Change Factors on Secondary Metabolites of Medicinal Plants in India

Sl. No	Plants	Geographical area	Medicinal properties	Climate change factor	Changes in Secondary Metabolites
1	*Catharanthus roseus*	Indian ocean island	Anticancer, astringent, and antibacterial	Elevated CO_2	Increase in total alkaloid and total phenolic content[36]
2	*Picrorhiza kurroa*	Himalaya	Treats liver, upper respiratory tract disorders	Elevated CO_2	Increased picroside-I and picroside-II contents in rhizomes[37]
3	*Zingiber officinale*	South west and North east India	Cold, nausea, arthritis, migraines, and hypertension treatments	Elevated CO_2	Higher accumulation of phenolics and flavonoids[38]
4	*Hypericum perforatum*	Western Himalayas	Anti-oxidant, anti-bacterial, and neuroprotective	Elevated CO_2	A decline in hypericin content[39]
5	*Ginkgo biloba*	Central Himalayan mountains	Treats asthma, bronchitis, Alzheimer's disease	Elevated CO_2 and ozone	Elevated quercetin aglycone and reduced bilobalide levels[40]
6	*Sida cordifolia*	Tropical and sub-tropical regions	Anti-inflammator, analgesic, hepato-protective	Ozone	Enhanced synthesis of stigmasterol, b caryophyllen, alkanox, and caryophyllene oxide[41]
7	*Salvia officinalis*	North Western Himalaya	Anti-inflammatory, anti-allergic, antifungal, and antiseptic	Ozone	Increased rosmarinic acid, gallicacid and caffeic acid levels[42]
8	*Withania somnifera*	Semi-arid, Deccan Peninsula	Sedative, hypnotic, anti-inflammatory	Cold stress	Increased production of withanolides[43]
9	*Ajuga bracteosa*	Sub-Himalayan tract, plains of Punjab and the upper Gangetic plain	Aids to cure cancer, diabetes, gastrointestinal disorders, urinary disorders, tuberculosis	Low temperature	Higher concentrations of phenylpropanoids [44]
10	*Mentha piperita*	Indo-Gangetic plain, Himalayas	Cures indigestion, antispasmodic, diuretic, antiemetic, mild sedative, relieves irritation	Elevated temperature	Reduced flavonoids, phenolics; increased tannin, terpenoid contents[45]
11	*Coleus species*	Western Himalayas, Nilgiri Hills	Treats digestive disorders, dysentery	Salinity	Maximum terpene content, increased levels of anthraquinones, cardiac glycoside, saponins etc[46]
12	*Centella asiatica*	Eastern Himalaya	Used to treat bronchitis, leprosy, fever, asthma	Salinity	Elevated levels of phenolics, flavonoids, terpenoids, alkaloids[47]

atmospheric CO_2 levels, largely due to human activities, poses a significant threat to plant life since the industrial revolution. [33] Medicinal plants, known for their adaptability to varying environmental conditions, often rely on secondary metabolites for their pharmacological properties, although fluctuations in these metabolites may affect their therapeutic efficacy.[34]

For instance, *Catharanthus roseus* possesses anticancer and antibacterial properties and is mainly used in treatments for leukaemia. Exposure to elevated CO_2 levels has been found to increase the alkaloid and phenolic content in this plant, likely due to enhanced activity of key enzymes in the phenylpropanoid pathway. [36] Similarly, *Ginkgo biloba,* known for its use in treating Alzheimer's disease, experiences changes in its terpenoid profile when exposed to high CO_2 and O_3 concentrations, leading to alterations in specific compound levels. [40]

Endangered medicinal plants like *Picrorhiza kurroa* (*Katuki*) from the Himalayan region exhibit changes in secondary metabolite accumulation, with elevated CO_2 levels affecting the content of compounds like picroside-I and picroside-II. [48] *Zingiber officinale* (*Sunthi)* shows increased phenolic and flavonoid content in response to atmospheric CO_2 enrichment.[38] *Hypericum perforatum*, found in the temperate western Himalayas and utilized for various medicinal purposes, displays fluctuations in hypericin content[49] based on temperature and CO_2 levels, highlighting the intricate relationship between environmental factors and secondary metabolite production in medicinal plants. An increase in ozone levels in the troposphere poses a threat to crops, including medicinal plants like *Sida cordifolia* (*Bala*), commonly cultivated in tropical and subtropical regions of India where elevated ozone concentrations are observed. This plant, known for its medicinal properties such as anti-inflammatory and hepato-protective activities, contains biologically active components like stigmasterol and â-caryophyllene. [41] Exposure to elevated ozone levels resulted in increased activity of certain metabolites like stigmasterol and â-caryophyllene in the leaves of *Sida cordifolia* compared to control plants, although variable responses were noted in terpenes in both leaves and roots. The concentration of secondary metabolites may be influenced by atmospheric ozone through mechanisms such as inhibition of carbohydrate accumulation or activation of defence signalling pathways.

Low temperature is another critical environmental factor that can influence the production of secondary metabolites in *Withania somnifera* (*aswagandha)*. [43] Exposure to cold temperatures led to increased accumulation of withanolides in both leaves and roots of *W. somnifera*, which may serve as a mechanism for scavenging reactive oxygen species (ROS). During cold treatment, roots initially showed a decrease in withanolide-A content on the first day but recovered thereafter, while withanone content increased in leaves on the first day and then decreased until the fifth day before entering a recovery phase. Additionally, withaferin A content in leaves steadily increased over the 7-day cold treatment period, indicating its protective role against cold stress. This increase in withanolides content may be attributed to enhanced accumulation and expression of antioxidant enzymes, along with the regulation of genes involved in the withanolide metabolic pathway during cold stress. The research findings indicated that exposure to a temperature of 15°C resulted in higher concentrations of phenylpropanoids such as cinnamic acid, caffeic acid, and quercitol in the samples, activating the antioxidant defence system of plants to counteract stress stimuli.[44] Conversely, higher temperatures suppressed the production of ginsenoside in *Panax quinquefolius* cell cultures. [50] When *Mentha piperita* (Mint) and *Catharanthus roseus* plants were exposed to high temperatures (35°C) for seven and fourteen days, there was a decrease in secondary metabolites levels including total phenolics, flavonoids, and saponins. However, other active

compounds like tannins, alkaloids, and terpenoids significantly increased at the same temperature[46], serving as key signalling components that modulate plant response mechanisms. The increased production of metabolites helps plants protect cellular and membrane structures under stressful conditions.

The escalating natural and anthropogenic activities have led to salinity problems that alter plant physiology and metabolism, thereby affecting overall growth and development. Excessive fertilizer usage, irrigation with low-quality water, and desertification contribute to soil salinity in cultivated areas.[51] Besides affecting growth and productivity, high salt concentrations also influence the composition of secondary metabolites in medicinal plants.[52] Coleus, valued in India for its therapeutic properties in treating digestive disorders and dysentery[53], was studied to investigate the effects of salinity on the accumulation of bioactive compounds. Various secondary metabolites including flavonoids, phenols, tannins, lignins, alkaloids, steroids, cardiac glycosides, anthraquinones, saponins, and terpenes were quantitatively estimated in leaves, stem, and roots of *Coleus* species subjected to salinity stress. Moderate salinity treatments resulted in the maximum accumulation of secondary metabolites, particularly terpenes, while higher salt concentrations led to a decline in their levels.[46] Increase in secondary metabolite accumulation during salinity stress may be attributed to the induction of enzymatic activity. *Centella asiatica* (*Mandookaparni*), which grows in marshy areas across India up to an altitude of 200 m, was exposed to various salinity treatments. Higher amounts of phytochemicals including phenolics, flavonoids, terpenoids, alkaloids, and saponins were detected in *C. asiatica*[48] compared to the control when subjected to different levels of salinity. The production of phytochemicals in response to salinity stress may serve as a mechanism for regulating osmotic balance and maintaining membrane fluidity in plants. [47]

CONCLUSION

The growing popularity of Ayurveda has spurred increased interest in medicinal herbs and natural remedies, leading to a projected growth in the plant-based drug market. Medicinal plants exhibit a rich diversity of secondary metabolites crucial for treating various acute ailments. However, the exploitation of natural resources by pharmaceutical companies has led to the depletion of medicinal plant populations and habitat destruction, exacerbated by factors like global warming and deforestation. However, the shifting climate poses a significant threat to these plants, especially those endemic to specific regions like the Himalayas and Western Ghats. Secondary metabolites, such as terpenoids and alkaloids, play crucial roles in plant defence mechanisms and have various pharmacological activities beneficial for human health. Endemic species, with their limited geographic range, are particularly vulnerable to extinction due to climate change-induced stressors such as temperature fluctuations, elevated CO_2 levels, and salinity stress. These environmental changes disrupt the normal physiology of medicinal plants, impacting the synthesis of biologically active compounds like phenolics, terpenoids, alkaloids, and saponins. While elevated CO_2 levels may enhance secondary metabolite synthesis in some plants, rising temperatures pose threats to species adapted to cold climates, potentially leading to their extinction. Understanding the molecular responses of medicinal plants to climate change is imperative, considering multiple factors at play. As medicinal plants are essential for human livelihoods, conservation efforts and climate change mitigation strategies are crucial to ensure their sustainable use and preservation for future generations.

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