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Climate Change-Induced Alterations in Bioactive Compounds of Medicinally Important Plants

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Abstract

Climate change has been a serious environmental factor affecting the growth, behavior, distribution, and chemical composition of medicinal plants. The changes in rainfall (precipitation), temperature, humidity, carbon dioxide level, and harsh weather conditions can have detrimental effect on plant metabolic activities. These changes in the environment can either enhance or suppress the production of biologically active (or otherwise known as bioactive) compounds like alkaloids, flavonoids, terpenoids, phenolics, and other chemical compounds present in the plant, which are important for their medicinal value. When various plant species undergo stress, they produce certain type metabolites or phytochemical compounds which is specific for that plant. While others produce lower amounts of these plant-specific metabolites, they can differ greatly in their healing attributes and/or effectiveness. In addition, environmental changes can also affect where plants grow i.e. their distribution, and also their life cycles, and their relationships with pollinators, pests and other plants which ultimately leads to the modification of their chemical makeup and composition. Understanding these effects is essential for finding ways and techniques to protect the diversity of medicinal plants and maintain the consistency of their healing properties. Hence, extensive research on how medicinal plants respond to climate change is required to support traditional medicine and the pharmaceutical industry in the future and eliminate research gaps.

Introduction

Plants produce a range of chemical compounds, categorized as secondary metabolites (or specific metabolites or "bioactive" molecules), that allow them to interact with their environment and are the chemical basis of many traditional and modern medicines [1, 2]. The concentration and composition of these metabolites is heavily influenced by environmental conditions. Climate change (induced by humans in this case) has the potential to alter the therapeutic profile of medicinal plant species, where they grow, and the manner of use in a way to reduce harm to the environment [3]. It is more important for industries dealing with herbal and natural products, public health, and biodiversity to recognize these effects

Recent comprehensive reviews and experimental studies have demonstrated both expected trends, e.g. CO_2 typically increases carbon-based phenolics, and complex species and compound-specific effects in response to the multiple interacting environmental stressors [4].

Human health has relied on medicinal plants and their naturally derived metabolites for millennia — they are the foundation of healthcare systems (both traditional and modern) — and human herbal and herbal medicinal products represent a vast reservoir of bioactive secondary metabolites, the very backbone of near 80% of modern pharma products and innumerous previous and contemporary traditional treatments [5]. Plants synthesize these compounds (e.g. alkaloids, phenolics), as well as terpenoids, flavonoids, glycosides, saponins, etc. as part of plant adaptive answer to its environmental cues and stressors [6]. Unlike primary metabolites, which are essential for plant growth and development, secondary metabolites play specialized roles in defense, signaling, and environmental adaptation. Their production is tightly regulated by genetic, physiological, and ecological factors, making them highly sensitive to fluctuations in environmental conditions [7].

Over the last few decades, climate change has taken a huge toll on the environment, globally affecting terrestrial ecosystems. Its primary causes include human activities (or anthropogenic) like release of greenhouse gases such as carbon dioxide, methane, and nitrous oxide [8]. The average temperature of the earth's surface has jumped up to about 1 - 1.5°C above the time before the industrial revolution, when societies relied heavily on manual labor and traditional ways of production than machine manufacturing. This warming is expected to increase in the future [9, 10, 11]. Also, changes in rainfall patterns, frequent occurrence of extreme weather conditions, high level of CO_2 in the atmosphere, building up of ozone (O_3) molecules are changing global vegetation patterns [12, 13]. These changes greatly affect plant physiology, development, and metabolic pathways that are involved in secondary metabolite production. Medicinal plants are easily affected by these changes because their healing or therapeutic properties depend mainly on precise amount and qualitative balance of secondary metabolites [14, 15]. Shortage of water and extreme temperatures can also activate biosynthetic pathways caused due to stress, ultimately leading to the accumulation of defensive compounds like terpenoids, tannins, and various alkaloids [16, 17, 18]. Climate change has many sides of effects on secondary metabolites. Metabolic adaptation caused by stress may increase the levels of various healing compounds in plants, possibly increasing healing attributes. While, too much or extended exposure to stress can disturb the balance between compounds, lower organic matter and yield, and even form toxic metabolites, making herbal products unsafe. These changes also affect pharmacological standardization because different amounts of bioactive compounds can change how strong, effective, and toxic a drug is. This is a problem for both traditional medicine and the modern pharmaceutical industry [14, 19, 20].

In addition, climate change can not only make changes to the chemical makeup of medicinally important plants, but can also interfere with their geographical distribution and genetic diversity [21].

Multiple plant species with lesser distributions (number) in an ecology can be outperformed or pushed to extinction as their habitats become unsuitable for their sustenance [22]. These areas include some of the greatest and largest biodiversity, including biodiversity hotspots like the Himalayas, Western Ghats, and tropical rainforests, which contains a significant portion of the world's medicinally active plants [23, 24]. The loss of these species could lead to the permanent loss of unique phytochemical properties, which would put a risk on the discovery of drugs in the future and lessen the effectiveness of traditional medicine knowledge systems [25]. Therefore, it is important to understand the relationship between climatic variables (like temperature, humidity, rainfall and wind speed) and secondary metabolites production for using medicinal plants sustainably in the future. To know any plant's responses to these changes in the environment, it requires not only physiological integration of the plant, but also an understanding of their metabolic activity, molecular biology, including the climate modeling. For example, transcriptomic and proteomic investigations are beginning to clarify the regulation of stress-responsive genes (e.g. phenylalanine ammonia-lyase, terpene synthases, and cytochrome P450s) under changing climatic contexts [26]. These findings are important during the process of identifying stress-resilient genotypes and developing climate-smart cultivation management practices to maintain or increase the bioactive compound output; even in changing environmental contexts. In many developing countries, medicinal plants are the primary source of health and well-being. It also plays a role as a major source of income for rural and village communities. The changes in growth patterns and biochemical profiles can therefore have negative impacts on public health, trade, and income. Disturbance in supply chains and regularity in raw materials can also affect global pharmaceutical markets, where standardized extracts and herbal formulations depend on known phytochemical content.

2. Climate change drivers relevant to plant secondary metabolism

Climate Change is a combination of complex environmental changes - including raised CO2 in the water, increased temperature globally, altered precipitation, drought, flooding, increased UV radiation, and increased ozone may all serve as direct or indirect drivers on plant physiology, metabolism and the production of secondary metabolites (fig. 1). These drivers each have an individual, yet inter-related effect on plant physiology and metabolism. Due to their high sensitivity to environmental conditions, plants that produce medicinally useful compounds often respond to these stresses by altering the production of related bioactive compounds that may function as defense or signaling molecules [6].

2.1 Elevated Atmospheric CO_2:

The increase in CO_2 levels increases the rate of photosynthesis and the uptake of carbon in plants, which increases the Carbon to Nitrogen (C: N) ratio. This commonly helps in the making of carbon-based secondary metabolites (e.g., phenolics, flavonoids, tannins, etc.) and decreases the production for nitrogen-based secondary metabolites (e.g., alkaloids).

Subsequently, the changes in atmospheric CO_2 can affect the therapeutic value of medicinal plants through differences in potency and chemical stability [16, 27].

2.2 Temperature Increase:

Temperature, on the other hand, functions by controlling enzyme behavior and metabolism. Moderate warming can stimulate the production of certain secondary metabolites, especially terpenoids and phenolic compounds, as metabolic rates increases. However, exposure to extended periods of excessive heat stress will denature the main biosynthetic enzymes and reduce overall production of metabolites. E.g. species like *Mentha piperita* and *Lavandula angustifolia* show significant variation in essential oil character when exposed to high temperatures [28].

2.3. Drought and Altered Precipitation Patterns:

Droughts also have significant effect on secondary metabolism. In moderate drought conditions, the content of secondary metabolites such as flavonoids, phenolic acids and certain alkaloids increases, which provides defense against oxidative stress. When drought is severe or continues for an extended period of time, it affects the plant by reducing its growth and development, which thereby reduces the quantity of biomass and yield of secondary metabolites [29].

2.4. Increased UV-B Radiation:

Exhaustion of ozone layer and alteration in the composition of atmospheric elements has caused the earth to be much more exposed to Ultraviolet-B. UV-B acts as both a stressor and a signal, inducing the biosynthesis of UV-absorbing compounds such as flavonoids and phenolics, which protect plant tissues from radiation damage. Elevated UV-B exposure often correlates with enhanced antioxidant properties in medicinal species [19].

2.5. Elevated Ozone Levels:

Ozone existing in the ground-level acts as a strong oxidant (oxidizing agent), causing oxidative stress and changes secondary metabolism. While moderate ozone levels may stimulate antioxidant compound production, chronic exposure damages chloroplasts and reduces photosynthetic efficiency, indirectly suppressing metabolite accumulation [18].

2.6. Salinity and Sea-Level Rise:

Salinity stress is becoming more noticeable in coastal regions where little or no rain occurs.

This is due to increase in sea level and degradation of soils. Salinity causes osmotic and ionic stress responses, leading to buildup of molecules that help organisms to survive in extreme conditions, as well as the accumulation of secondary metabolites such as saponins and phenolic glycosides, but excessive salinity often inhibits growth and metabolic balance [25].

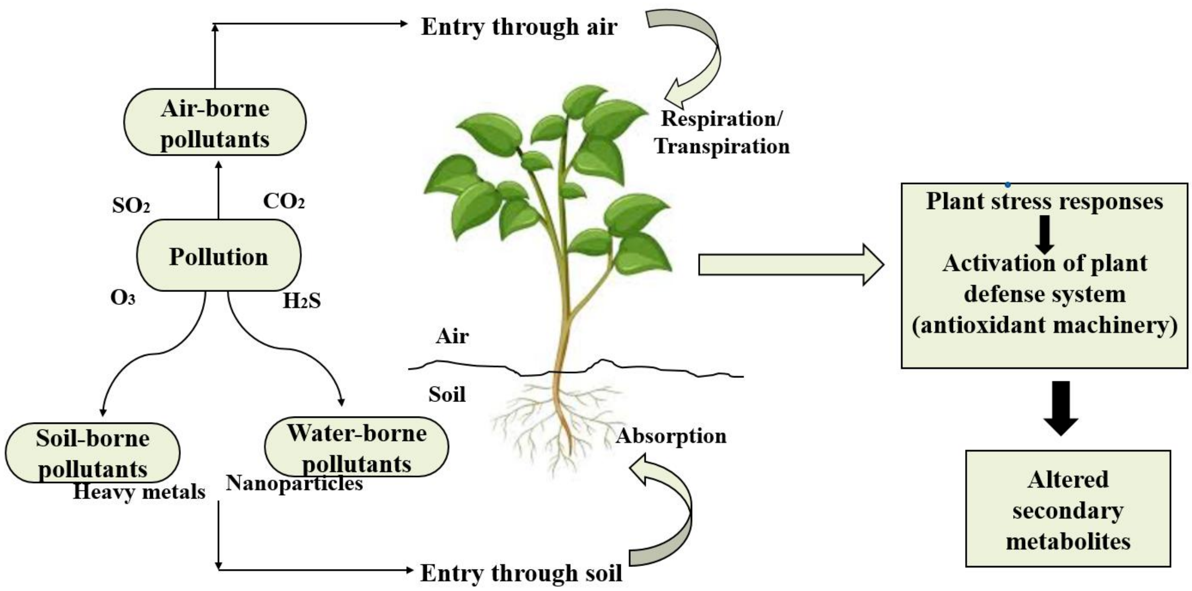

Figure 1. Effect of pollutants uptake from the environment by medicinal plants.

3. Mechanisms relating climate factors to secondary metabolite production

The production of secondary metabolites in plants is a highly advanced and sophisticated process and is controlled by physiological, genetic, and environmental factors. These factors include increased CO_2 in the atmosphere, temperature, drought, ozone, and UV radiations. The impacts of these factors are very much complex and involve various biochemical and molecular processes [3].

3.1 Carbon–Nitrogen Balance (C: N Ratio) and Resource Allocation

The increase in atmospheric carbon dioxide increases the carbon fixation and increases carbohydrate production during photosynthesis. This results in a higher carbon-to-nitrogen (C: N) ratio in plant tissues.

The Carbon–Nutrient Balance (CNB) hypothesis proposes when plants have access to an excess amount of carbon and restricted nitrogen, they transfer some carbon into the production of carbon-based secondary metabolites (CBSMs, such as phenolics, flavonoids, tannins, and terpenoids). Then, they may also lead to the production of nitrogen-based compounds in lower amounts. Later, these changes in nutrient balance result in alteration in pathways and the quantity of bioactive compounds produced by plants [16, 17].

3.2 Oxidative Stress and Reactive Oxygen Species (ROS) Signaling

Stress caused by climate factors such as drought, high temperature, and ozone exposure can activate the production of excess reactive oxygen species (ROS), including hydrogen peroxide (H_2O_2) and superoxide radicals [30].

These reactive oxygen species in plants not only worsen the stress, but also acts as signaling molecules to activates defence pathways. In response to this, plants produce antioxidant secondary metabolites (phenolics, flavonoids, carotenoids) and antioxidant enzymes which enhances redox homeostasis. On the other hand, activation of secondary metabolism caused by certain stress typically leads to the accumulation of bioactive compounds with high pharmacological activities [29, 18].

3.3 Hormonal Regulation and Stress-Responsive Pathways

Plant hormones such as jasmonic acid, salicylic acid, ethylene, and Abscisic acid (ABA) act as signaling mediators between environmental stress and secondary metabolism [31]. E.g., Jasmonic acid activates genes that are related to alkaloid and terpenoid production under stress. While Salicylic acid helps in the production of phenolic and flavonoid compounds during pathogen defense, and Abscisic acid controls the accumulation of organic molecules that helps organisms to survive extreme osmotic stress (also called as osmoprotectants, e.g., glycosides and proline) during drought and heat stress. When these hormonal pathways interact with each other, they help the plant decide how much secondary metabolites to produce depending on how strong and how long the stress is. [20, 27].

3.4 Gene Expression and Enzyme Regulation

Changes in climate can impact gene regulation, affecting both the transcription and post-transcription processes that control the enzymes involved in biosynthetic pathways. Some of the key examples include:

- Phenylalanine ammonia-lyase (PAL) and chalcone synthase (CHS) for phenolics and flavonoids.
- Terpene synthases (TPS) and cytochrome P450s for terpenoids.
- Strictosidine synthase for alkaloids. Elevated CO_2, temperature, or drought can upregulate or repress these enzymes via transcription factors (TFs) such as MYB, bHLH, and WRKY families. Moreover, epigenetic modifications (DNA methylation, histone acetylation) have been observed to play roles in stress-induced metabolic reprogramming, although this area remains underexplored in medicinal species [17, 19].

3.5 Source–Sink Dynamics and Phenological Shifts

Climate change changes carbon allocation among "source" tissues (photosynthesizing leaves) and "sink" tissues (roots, fruits, flowers). During periods of influence, plants can reallocate resources away from growth and toward defending and sustaining life, resulting in the accumulation of metabolites in certain organs to higher concentrations than plants under optimal conditions.

Furthermore, phenological changes (e.g., sooner flowering and shorter growth cycles) will alter the timing of maximum accumulation of secondary metabolites (fig. 2). The amounts of phenolics and alkaloids may peak in different developmental stages of crops depending on altered environmental cues [28].

3.6 Interaction of Multiple Stress Factors

In natural environments, it is very rare for multiple stressors to not interact with one another. Elevated CO_2, heat, and drought may have synergistic or antagonistic effects on secondary metabolism throughout the interactions. For example, the phenolic increases seen with CO_2 may be lost through degradation driven by heat, or phenolics may be limited by substrate availability during drought conditions. These types of interactive effects inhibit our ability to generalize predictions, even when undertaking complex multi-factorial studies and ultimately leading to field validates [17, 18].

3.7 Evolutionary and Adaptive Mechanisms

Prolonged exposure to new climatic conditions may result in adaptive evolution in plant populations, leading to genotype shifts in their capacity to biosynthesize secondary metabolites. Natural selection may favor those chemotypes that are more resilient to abiotic or biotic stress, and over time, will gradually influence the phytochemical diversity of certain medicinal plant species [25].

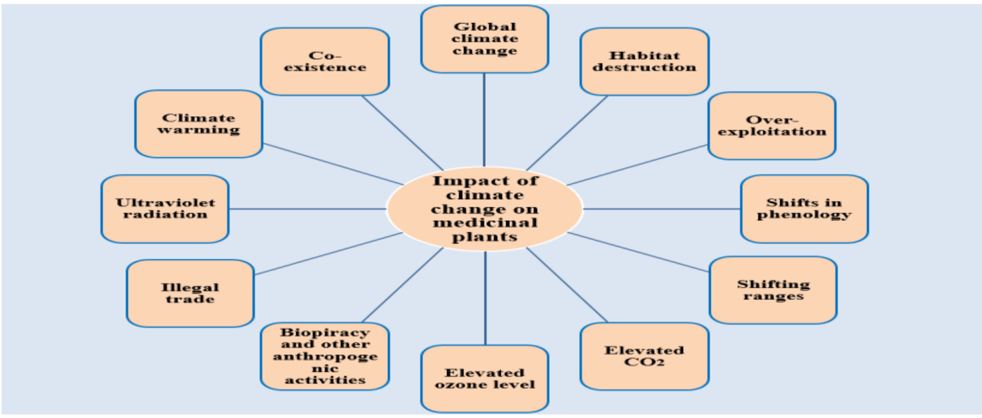

Figure 2. Climatic factors causing a threat to medicinal plants.

4. Effects on major classes of bioactive compounds

Climate change exerts diverse and compound-specific effects on the production, accumulation, and composition of secondary metabolites in medicinal plants. These bioactive compounds such as phenolics, flavonoids, terpenoids, alkaloids, glycosides and saponins are the main components of medicinal plants that helps in the therapeutic effectiveness of herbal medicines. Factors such as high CO_2 levels, changes in temperature, stress due to unavailability of water, and

UV radiation affect the enzymes, precursors, and signaling pathways involved in their production. The following describes how each major classes react to changing climatic conditions.

4.1 Phenolics and Flavonoids

Phenolics and flavonoids are compounds that are rich in carbon and are produced through the phenylpropanoid pathway. These compounds function primarily in defense and antioxidation of plants. Stresses caused by environmental factors such as drought, UV-B radiation, ozone exposure, and elevated CO_2 that increase oxidative pressure help in higher production levels. Phenolic and flavonoid content increases when there is a higher concentration of CO_2. This occurs due to an excess amount of fixed carbon and activation of enzymes like phenylalanine ammonia-lyase (PAL) and chalcone synthase (CHS). UV-B radiation also helps in the accumulation of flavonoids (E.g., *Ginkgo biloba* leaves) as these compounds act by absorbing UV light and protecting the tissues from extended exposure to light (especially high intensity lights) [32]. Drought and temperature stress lead to higher flavonoid levels as part of the oxidative stress defense response.

However, total phenolic content or production is reduced when severe or extended stress is endured. This reduction in the phenolic content occurs due to decreased biomass accumulation. E.g., moderate level of water stress increased total phenolics and antioxidant activity in *Ocimum basilicum* (Sweet basil) and *Rosmarinus officinalis* (Rosemary), while severe or higher level of stress reduced both yield and compound diversity [19, 28].

4.2 Terpenoids

Terpenoids belongs to one of the largest classes of secondary metabolites and are produced through different pathways such as mevalonate (MVA) pathway and methylerythritol phosphate (MEP) pathway [33]. Terpenoids forms the core, the main compound of various essential oils, resins, and plant volatiles (organic compounds that plants release into the air that can be easily evaporated). Temperature and unavailability of water strongly affect terpenoid production and volatilization (the process by which a substance changes from a liquid into a vapor). Moderate-level of stress can also help in increasing essential oil concentration and change its chemical composition, thereby enhancing certain monoterpenes while suppressing others. Increased CO_2 level can either raise or lower terpenoid concentrations, depending on how carbon is allocated and how terpene synthase enzymes are regulated. High-intensity light and UV radiation can also modify terpenoid profiles by influencing the availability of precursors in chloroplasts. E.g., rise in temperature can increase menthol concentration but also decreased menthone and pulegone in *Mentha piperita* (peppermint). This affects and alters both aroma and therapeutic properties of the plant. In the same way, *Artemisia annua* shows varying responses of artemisinin content under combined CO_2 and temperature changes [18].

4.3 Alkaloids

Alkaloids are chemical compounds that contains nitrogen and are mainly composed of amino acids and plays an important role in the environment as defense agents. Their production is highly dependent on nitrogen availability and regulations in hormone. This dependence of alkaloids makes them particularly sensitive to reduction in nitrogen caused by CO_2 and plant stress hormones like jasmonic acid and ethylene. When CO_2 is higher in concentration, lower amount of nitrogen occurs in the tissues which may lower alkaloid concentration in some species of plants, for example *Papaver somniferum* (morphine) and *Atropa belladonna* (atropine). Droughts and herbivory stress (stress in plants caused by herbivore feeding) can activate jasmonic acid pathways, which in turn promotes alkaloid production in plants like *Catharanthus roseus* (vincristine, vinblastine) while also decreasing the production in plants like *Glycine max* (soybean) [34]. Extremely high Temperatures influence enzyme activity that drives alkaloid synthesis, which then leads to changes in both the amount produced and the type of alkaloids formed.

4.4 Glycosides and Saponins

Glycosides are chemical compounds that occur naturally in plant tissues. These compounds consist of sugars are attached to bioactive aglycones, which affects their solubility, transport, and pharmacokinetic behavior. Saponins, on the other hand, is a subcategory of glycosides which play vital roles in stabilization of membrane and defend plants against pathogens.

Drought and extreme saline conditions can increase saponin production and accumulation, as seen in *Panax ginseng* (Asian ginseng) and *Glycyrrhiza glabra* (Liquorice) [35]. This results from increased expression of genes involved in triterpenoid saponin biosynthesis. Increased CO_2 and heat stress can change glycosylation patterns, which in turn affects the polarity and biological activity of the compounds formed. These changes can either enhance or decrease the medicinal effectiveness of plants that are rich in glycoside. depending on how aglycone–sugar interactions are modified under stress [18, 25].

4.5 Tannins and Other Polyphenols

Tannins are high-molecular weight polyphenols that participate in defense against herbivory and microbial attack. Their concentrations may rise when exposed to elevated CO_2, UV, and drought, in line with the carbon–nutrient balance hypothesis. However, when tannin concentrations are excessive, astringency and taste may be adversely affected in herbal products. Pharmacology: Higher concentrations of tannins may enhance antioxidant and antimicrobial activity; on the other hand, it may limit the bioavailability of other nutrients or drugs if consumed at the same time [19, 16].

5. Species-level examples and case studies

5.1 *Withania somnifera* (Ashwagandha) — Heat and Water Stress

Withania somnifera is capable of synthesizing withanolides which are steroidal lactones with both anti-inflammatory and neuroprotective properties. Under high heat and drought conditions, the plant produces higher amounts of withanolide A and withaferin A that coincide with increased oxidative stress signaling as well as the activation of secondary metabolism. However, prolonged stress or stressors that are too great reduce growth and yield of total compounds [36, 37, 38].

Key observation: The signaling involved with stressors can increase withanolide biosynthesis, however, extreme amounts of stress in the environment will bring about reductions of biomass and therefore total yield of pharmacological compounds.

5.2 *Glycyrrhiza glabra* (Licorice) — Salinity and Water Stress

In *Glycyrrhiza glabra*, salinity stress enhances glycyrrhizin accumulation — a triterpenoid saponin with anti-inflammatory and antiviral activity — as a protective response against osmotic imbalance. However, sustained high salinity eventually decreases plant vitality and overall metabolite productivity [39].

Key Observation**:** Mild salinity acts as an elicitor for glycyrrhizin synthesis, but excessive salt concentrations compromise yield and plant health.

5.3 *Hypericum perforatum* (St. John's Wort) — Multifactorial Environmental Influence

Hypericum perforatum, a perennial herbaceous plant, shows a complex relationship with environmental factors and is known and valued for its antidepressant compound hypericin used in mild-to-moderate depression. When this plant was studied under controlled conditions, it was found that light intensity, carbon dioxide concentration, and water availability together effect the levels of hypericin and hyperforin. When *H. perforatum* undergoes moderate-level drought, phenolic compounds are accumulated in higher amount due to the activation of the phenylpropanoid pathway activated due to stress. But when excessive heat or continuous water deficit is tolerated, it leads to reduced overall weight (biomass) and reduction in yield of bioactive compounds [40].

Key Observation: In *H. perforatum*, the production or biosynthesis of secondary metabolite is dependent on light intensity and water availability. When plants endure minimal or moderate level stress it enhances bioactive compound production, but when exposed to extreme conditions it can be damaging.

5.4 *Centella asiatica* (Indian Pennywort or Gotu Kola) — Effect of Elevated CO_2

Centella asiatica is commonly used as a medicinal herb and is rich in triterpenoids and phenolic compounds. It is also highly sensitivity to variation in CO_2 in the atmosphere.

Studies have shown that when the level of CO_2 increases, the total triterpenoid and phenolic content increase due to improved carbon assimilation and increase in the production of enzymes such as squalene synthase and phenylalanine ammonia-lyase (PAL). Studies on this very plant have stated that when CO_2 is present in higher amounts, it significantly improves antioxidant activity and secondary metabolite concentration in *C. asiatica*. This predicts that in future climate conditions, when atmospheric CO_2 increases due to human activities, it may improve its healing abilities. But when there is excessive accumulation of certain compounds, it might also change its pharmacokinetic balance and lead to changes that is needed for standard dosage preparation. [41, 42].

Key Observation: When there is increase in CO_2, it increases the triterpenoid and phenolic production. This occurs due to higher rate of photosynthesis and carbon flux. However, the changes in their composition may potentially affect their therapeutic value.

5.5 *Artemisia annua* (Sweet Wormwood) — Interactive Effects of CO_2 and Temperature

Artemisia annua, also known as sweet wormwood, is the source for artemisinin (an anti-malarial compound). This plant shows different responses when exposed to climatic factors. When there is moderate increase in atmospheric CO_2 and temperature increases the buildup of artemisinin by increasing precursor availability in the terpenoid biosynthetic pathway. However, exposure to extended period of high temperatures, i.e. beyond the plant's optimum (30–35°C), can prevent key enzymes like amorpha-4,11-diene synthase (ADS), thereby reducing the content of artemisinin. Studies have shown that high levels of CO_2 may partially decrease stress caused by temperature by increasing the rate of photosynthesis and growth rate, but the overall impact changes with species and environmental conditions [43, 44].

Key Observation**:** *A. annua* shows dual response: moderate warming increases artemisinin production, while excessive heat suppresses enzyme activity.

5.6 *Panax ginseng* (Asian Ginseng) — Drought and Temperature Stress

Panax ginseng produces ginsenosides, triterpenoid saponins known for their adaptogenic and immunomodulatory properties. Drought stress raises total ginsenoside content, particularly Rb1 and Rg1, due to the activation of oxidative stress-related pathways and increased jasmonic acid signaling. However, extended drought or high level of heat stress reduces root overall weight (biomass). It has been observed similar patterns under combined stress, where ginsenoside composition changed, indicating selective pathway activation [45, 46].

Key Observation: Mild stress enhances synthesis of ginsenoside, but when excessive environmental stress or pressure is exerted, it reduces total yield and changes compound ratios vital for their healing ability.

5.7 *Mentha piperita* (Peppermint) — Drought-Induced Essential Oil Modulation

Mentha piperita (commonly called as Peppermint) produces monoterpenes, specifically menthol and menthone, which are the key substances used in pharmacology and aromatherapy. Little to moderate drought stress activates monoterpene synthase genes in glandular trichomes (multicellular plant hairs), which increases essential oil concentration and the amount of menthol present in it. However, severe drought conditions reduce the biomass, leading to a lower overall oil yield [47].

Key Observation**:** Mild drought increases the value of essential oils and menthol yield, whereas extended periods of droughts reduce biomass and total oil productions.

5.8 *Ocimum basilicum* (Basil) — Heat and CO_2 Combined Effects

Ocimum basilicum is a key medicinal and aromatic herb that is rich in linalool and eugenol. When there is high concentration or increase in CO_2, and is combined with moderate heat, it improves the rate of photosynthesis and phenolic production, which ultimately leads to higher essential oil amount and stronger antioxidant property of the plant. Exposure to extreme heat (i.e. over 38°C), however, disturbs the stability of enzymes and reduces the chlorophyll content of the plant [48, 49].

Key Observation: Combined CO_2 enrichment and moderate heat improve essential oil yield and antioxidant potential, but excessive temperature decreases productivity.

5.9 *Rosmarinus officinalis* (Rosemary) — Phenolic Response to CO_2 and Drought

Rosemary contains phenolic diterpenes (carnosic acid, rosmarinic acid) with strong antioxidant activity. When this plant undergoes elevated CO_2 level and moderate drought, it increases its phenolic concentration. However, severe drought can reduce the photosynthetic rate and overall weight, ultimately reducing the total bioactive compound production [50].

Key Observation: Under combined effects of high atmospheric CO_2 level and mild drought, the plant increases phenolic antioxidants, but extreme stress lowers productivity and reduces the production of various compounds.

5.10 *Catharanthus roseus* (Madagascar Periwinkle or Bright Eyes) — Water Stress and Alkaloid Pathway Activation

Catharanthus roseus is supposedly known to produce anticancer compounds such as vincristine and vinblastine. During drought seasons this plant induces jasmonic acid signaling pathway. This signaling pathway then functions by increasing the activity of enzymes like tryptophan decarboxylase (TDC) and strictosidine synthase (STR), which is involved in the production of alkaloids. But when there are severe cases of drought and/or nitrogen unavailability, it acts by decreasing the availability of precursors and reduces the total amount of alkaloids it produces [51].

Key Observation: Moderate drought improves alkaloid buildup through stress signaling, but prolonged stress impairs nitrogen assimilation and total productivity.

5.11 *Curcuma longa* (Turmeric) — Heat and Drought Effects on Curcuminoids

Turmeric (*Curcuma longa*) is used all over the world and is a major medicinal spice used in our day-to-day lives. Turmeric produces strong antioxidant and anti-inflammatory substances, known as curcuminoids, such as curcumin, demethoxycurcumin, etc.

When these plants undergo drought or water unavailability and high temperatures, it enhances the accumulation of these compounds to higher amounts as a response to oxidative stress. But in severe or extended exposure to heat and drought, the total rhizome biomass and yield of essential oil are reduced. When carbon dioxide is higher in the atmosphere, it further improves the production of curcumin [52].

Key Observation: Moderate stress enhances curcuminoid concentration, but extreme drought or heat significantly lowers rhizome yield and total extractable curcumin.

5.12 *Camellia sinensis* (Tea) — CO_2 and UV-B Influence on Polyphenols

Tea is an evergreen shrub popular in the South East Asian countries. It is rich is polyphenol flavonoids, including catechins, such as EGCG, ECG, and EGC. Under elevated CO_2 the total polyphenol and catechin content increases, while exposure to UV-B radiation can increase or enhance flavonoid synthesis (this acts as a protective mechanism against light). When excessive UV-B radiation is endured, it reduces the expansion of leaf and photosynthetic rate. This has a huge impact on the production of energy necessary for proper growth and development of the plant affecting tea quality [53, 54].

Key Observation: High CO_2 level and minor UV-B radiation enhances catechin concentration and tea quality, but high UV exposure reduces biomass and leaf productivity.

5.13 *Aloe vera* — Drought and Heat-Induced Secondary Metabolite Changes

Aloe vera is widely used for healing wounds, skin protection, and providing relief against burns. While this plant bears healing and protective properties, it is due to the presence of naturally occurring compounds known as anthraquinones. Anthraquinones may be of various types, e.g., aloin, aloe-emodin. Moderate drought increases anthraquinones buildup, while high temperature increases gel dehydration which decrease the total amount [55].

Key Observation: Moderate drought increases anthraquinone content, which assist in the plant's healing property, but extreme dehydration and heat stress compromise gel yield and therapeutic potential.

5.14 *Lavandula angustifolia* (Lavender) — Temperature and Water Deficit Impact on Essential Oils

Lavender is a perennial flowering plant known for its aromatic essential oil. The oil is rich in linalool and linalyl acetate used particularly for relaxation and aromatherapy. The intensity of the aroma increases when moderate drought occurs. This is because water unavailability can stimulate oil glands and production of compounds known as monoterpenes. When exposed to high temperature, it can change the particulate ratios and decrease yield [56, 57].

Key Observation: Moderate drought enhances essential oil quality and aroma, but excessive heat disrupts volatile composition and yield stability.

5.15 *Nardostachys jatamansi* (Spikenard) — Altitude Shift and Climate Vulnerability

Spikenard is a Himalayan herb that contains sesquiterpenes and iridoids (natural substances that shield neurons or nerve cells from injury, degeneration or even death). These plants are found at high altitudes ranging from 3000 to 5200 meters. Due to global warming, its habitat is shifting upward, reducing population density in lower altitudes. Moderate cold increases oil content, but temperature rise alters the ratio of key sesquiterpenes [58].

Key Observation: Altitudinal migration under warming climates affects both survival and essential oil composition, threatening medicinal and conservation value.

5.16 *Zingiber officinale* (Ginger) — Temperature and Water Stress on Phenolics

Ginger belongs to the flowering family of Zingiberaceae and is an aromatic spice. It is a rhizome (an underground stem) that is used as a condiment in cooking as well as in methods of traditional medicine. Ginger produces and stores antioxidant and anti-inflammatory substances such as gingerols (in fresh ginger) and shogaols (when dried). Environmental stress such as mild drought can enhance 6-gingerol content through the process of phenylpropanoid metabolism, while excessive heat (above 35°C) can lead to decreased growth and oil concentration [16, 59].

Key Observation: Moderate drought increases the concentration of phenolic antioxidants, whereas extreme heat or dehydration reduces biomass and total oil production.

5.17 *Echinacea purpurea* (Purple Coneflower) — CO_2 and Drought Effects on Caffeic Acid Derivatives

Echinacea purpurea, commonly called as Purple Coneflower, is native plant of Central and North America, and belongs to the family Asteraceae. This plant belongs to the family Asteraceae and produces caffeic acid derivatives like cichoric acid and echinacoside which regulates the body's immune system. When high CO_2 levels occurs in the atmosphere, the plant response by increasing phenolic production and antioxidant holding capacity. When Mild drought occurs, it increases cichoric acid accumulation, but prolonged stress decreases total root yield. When high atmospheric CO_2 level and mild to moderate drought occur together, their effects add up, though only to a point [60, 61].

Key Observation: Although higher carbon dioxide levels and mild drought can improve phenolic production and antioxidant potent, prolonged stress causes the plant to lose biomass and produce lower therapeutic compound production.

5.18 *Tinospora cordifolia* (Giloy) — Heat and Water Stress on Alkaloid Profiles

Tinospora cordifolia consists biologically active compounds such as alkaloids and diterpenoids like tinosporine and berberine present in the stem and root.

During drought seasons, the production of alkaloids is improved which in turns increases responsiveness of the body's immune system. But, prolonged exposure to heat and drought can reduce leaf chlorophyll content and stem growth and development, which can drastically reduce alkaloid synthesis [19, 62, 63].

Key Observation: Mild drought enhances alkaloid accumulation, but long-term stress reduces biomass and total phytochemical content.

5.19 *Phyllanthus emblica* (Amla) — Temperature and CO_2 Impact on Antioxidant Compounds

The fruits of Amla are rich in vitamin C, gallic acid and ellagic acid. When there is an increase in carbon dioxide level, total phenolic and ascorbic acid content increases which in turn increases the antioxidant property. However, rising temperatures can accelerate fruit ripening/maturation while also reducing shelf life. In severe cases of drought, phenolic content can initially increase but decrease under prolonged exposure [17, 64].

Key Observation: Moderate rise in CO_2 can improve antioxidant substances, while excess heat can reduce the fruit quality and stability after harvesting.

5.20 *Boswellia serrata* (Indian Frankincense) — Drought and Heat on Resin Yield

Boswellia serrata is a tree prevalent to India. It produces boswellic acids known for its anticancer and anti-inflammatory properties. Moderate level stress can enhance and improve resin secretion and boswellic acid concentration in the plant itself, which activates secondary metabolism. When this plant is exposed to extended high temperature (heat) and low rainfall, it can lead to early leaf senescence and reduced resin secretion [25, 65, 66].

Key Observation: When the plant occurs in minor drought conditions, it enhance the production of boswellic acids, but in long term exposure to dryness, it lowers the resin production and reduces the lifespan of the plant.

6. Consequences for pharmacology, safety and supply

6.1 Therapeutic efficacy and quality control

Changes in concentration or ratios of active compounds may alter potency and safety (dose–response), which also puts a barrier on the discovery and innovation of drugs. Standardization of herbal products faces new challenges if growing environments change compound profiles [67].

6.2 Toxicity and formation of unwanted metabolites

The increase in the concentration of secondary metabolites caused due to climate change is not always desirable. While most of the it might be beneficial, many of the plants used in local and traditional medicine consists of toxic compounds that possess a great risk if used incorrectly or excessively. Therefore, monitoring the levels of these compounds is necessary to ensure safety [14].

6.3 Biodiversity, distribution and conservation impacts

Environmental changes can lead not only to alteration in biodiversity, but also makes evident that such changes can affect the distribution of plants. Unfamiliar distributions of species in an ecology makes these a challenge for people to conserve these plants [68].

7. Mitigation, adaptation and research strategies

7.1 Agronomic and cultivation approaches

Climate change can affect yields, food quality and the overall nature of the produce and in order to counteract this challenge, farmers now invest in new technologies and strategies to lessen the effects of changing climate. These can include controlled cultivation (such as greenhouses, vertical farming, regulated CO_2/temperature), irrigation management, selection of resilient cultivars/chemotypes, and soil fertility management [69, 70].

7.2 Breeding, selection and biotechnology

Modern biotechnology and breeding techniques, including conventional breeding and tissue culture—which allows growth under controlled environment—can drastically improve the production of plants that are fertile and resistant towards biotic and abiotic stresses. Through the introduction of genetically modified crops or transgenic crops, it can be made possible to overcome the negative effects of climate change [71].

7.3 Conservation (in-situ and ex-situ) and ethical sourcing

There can be various methods of conserving biodiversity. These includes protected area systems, on-farm conservation, botanical gardens, gene banks, seed banks, cryopreservation, etc. These can help in the conservation of genetic diversity.

CONCLUSION

Climate change significantly impacts the chemical composition of medicinal plants, affecting their efficacy, safety, conservation and the livelihoods of communities dependent on them. While mild climate changes can increase the production of beneficial secondary metabolites such as phenols and flavonoids, severe stress can lead to reduced plant weight and limit metabolic pathways.

This change creates challenges for the pharmaceutical industry, as the efficacy and safety of plant-derived compounds can change dramatically with environmental changes. Furthermore, climate change threatens biodiversity and the survival of local medicinal plants, putting traditional medicine, especially in rural communities, at risk. To address these challenges, strategic measures such as controlled cultivation systems, biotechnology innovations like CRISPR, and improved research methodologies are necessary. These methods can help stabilize metabolite production and bring resilience to medicinal plants, providing opportunities for the discovery of new compounds and sustainable practices in herbal medicine production. The confluence of climate science, plant biochemistry and biotechnology highlights a new frontier for advancing medicinal plant research while addressing environmental challenges.

9. References

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