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Climate change and the future of medicinal plants research

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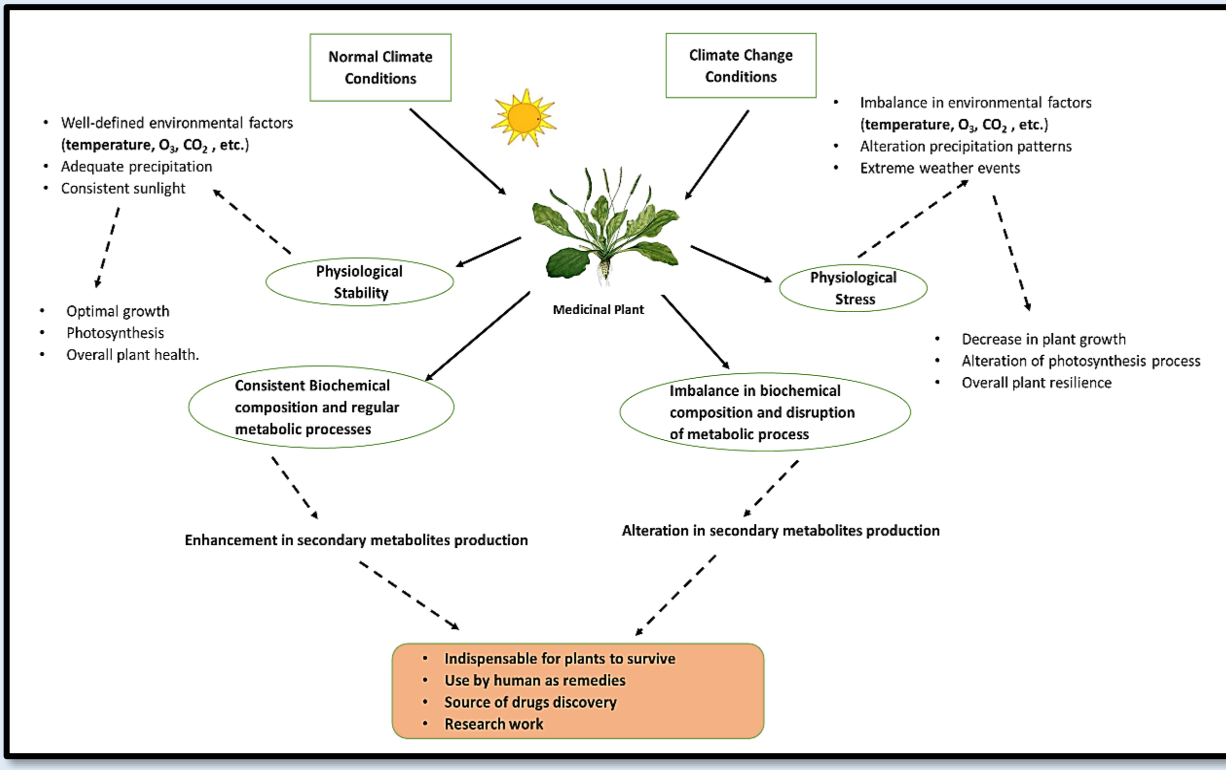
ABSTRACT

Due to their pharmaceutical properties and secondary metabolites, medicinal plants have played a crucial role in alleviating human suffering from various illnesses, disorders, and diseases. Along with other natural and artificial disasters, rapid climate change is one of the critical causes of the decline in wild medicinal plant species. Therefore, considering their significance in traditional medicine practices and economic value, investigating the potential consequences of climate change on medicinal plants is specifically relevant. This review aimed to investigate the diversity of species of medicinal plants within current climate scenarios. Additionally, it assesses the potential implications of climate change on the projected distribution of these species in subsequent scenarios and evaluates the possible impacts of these changes on the trajectory of future research in medicinal plants.

The distribution and life cycles of all vegetation, including medicinal plants, are significantly impacted by climate change. Additionally, future climate scenarios have been shown to affect the physiological performance of all vegetation worldwide. Various aspects related to climate change and its repercussions on medicinal plants are explored including the impact of increased carbon dioxide (CO_2) and ozone (O_3) levels, the effect of low temperature (Cold), climate warming, drought on the production of secondary metabolites, impact of threats on medicinal plants, and phenological changes. Each of these environmental factors influences the productivity and quality of different products and components of medicinal plants, either positively or negatively. Consequently, there is excellent complexity surrounding how climate change affects medicinal plants. Thus, for human survival on Earth, future researchers should carefully examine the interactions of various direct and indirect causes and their corresponding effects.

Keywords: Secondary metabolites, Climate change, medicinal plants, Phenology



INTRODUCTION

Climate change has emerged as one of the most important research challenges globally over the past 20 years [1]. Increasingly, climate change is being acknowledged as a significant challenge for both humans and all other living beings on the planet. A medicinal or pharmacopeial plant is defined as a plant that possesses compounds within one or more of its parts that have therapeutic properties, or which are precursors for the synthesis of useful drugs [2]. Medicinal plants are extremely crucial to human survival [3]. The regular course of human existence, agriculture, forestry, biodiversity, and ecosystem function are all negatively impacted by changing climatic circumstances [4]. Various sectors, including individual well-being, water and air quality, soil integrity, microbial ecosystems, plants and their medicinal elements, secondary metabolites, and food security, experience adverse effects due to climate change. Climate change is primarily driven by the growth in the world population, rapid industrialization, and the widespread utilization of chemical pesticides and fertilizers in farming [1]. Changing climatic conditions manifest through increased temperatures, cold spells, drought, and shifts in rainfall patterns.

Within the classification of medicinal and aromatic plants (MAPs), many different types of plants exist, comprising annuals, biennials, perennials, and so forth. These plants typically grow in diverse habitats and climates, with all of their parts being useful. According to Shrestha et al., medicinal and aromatic plants are instrumental in promoting human well-being through health and economic advantages [5]. In other words, throughout the development of human civilization, the recognition of various plant categories is attributed to their nutritional, therapeutic, remedial, and essential sustenance-contributing attributes vital for everyday existence. Within these plant categories, the medicinal plant group holds significant importance due to its secondary metabolites and pharmaceutical attributes [4,6], extensively employed across pharmaceutical, medical, cosmetic, and nutritional sectors [7]. According to Mohammadhosseini et al. [8], numerous reviews have suggested and argued for the remarkable effects of medicinal plants in the literature and scientific databases by citing their beneficial bioactive compounds, ethnobotany, conventional and folk medicine, promising biological and pharmaceutical properties, and other related features found in herbal plants.

The World Health Organization (WHO) reports that almost 80% of the Earth's population utilizes natural and traditional approaches for healing, thus employing medicinal plants in the process [1]. Currently, there are about 28,000 plant species known to have therapeutic applications worldwide [5], and about 3,000 of them are involved in regional, national, and international trade networks [9]. Additionally, there has been a rising demand for natural health products and herbal medicines in recent years, leading to the rapid expansion of MAPs trading worldwide [10]. However, their present extinction rate is 100 to 1000 times greater than the natural background extinction rate, indicating the potential loss of at least one crucial drug every two years [9]. A report from the World Health Organization reveals that Ayurveda authenticates the medicinal use of approximately 45,000 distinct plants belonging to over 21,000 plant species [11]. Research on how the distribution of species and the quality of medicinal plants under different climate conditions will, therefore, be essential to understanding and guiding the development of national strategies for the conscientious handling of medicinal resources [13-14]. Successfully executing this involves examining the ecological prerequisites of these plants and fostering awareness among decision-makers, stakeholders, and the public. The crucial aspect is assessing the effectiveness of these strategies in conserving species amidst changing climates, considering the anticipated shifts in the distributions of many species. This review aimed to investigate the diversity of species within current climate scenarios for all medicinal plants, investigate the potential consequences of climate change on the projected distribution of these species in future scenarios, and evaluate how it might impact the trajectory of future research in medicinal plants.

METHODS

An extensive search was carried out on articles published from 2017 to 2024. Case studies, technical notes, and instructional materials that were pertinent to the goal and are regarded as reliable sources of information in the field of medicinal plant research served as additional valuable sources of information. A literature search was conducted using Google, Google Scholar, PubMed, Web of Sciences, and Research Gate. To obtain relevant information, we used the following keywords: “(Medicinal plant) AND (Climate OR warming)”, “(Climate change) AND (Future research on medicinal),” or in various combinations thereof to pool as much literature search as possible. Moreover, to exclude research at this stage, we studied the abstracts of each of these publications to determine which were based on climate fluctuation and its impacts on the plant life cycle, particularly medicinal plants and their constituents known as secondary metabolites. We also searched the remaining documents for additional pertinent references that the initial search had overlooked.

REVIEW

Generality and possible causes of climate change: The interconnected systems of the sun, earth, and oceans collectively form the global climate [14]. Global climate is described as the average variability of significant amounts of particular variables (such as temperature, precipitation, or wind) over a long period, which can be anything from months to hundreds of millions of years. The phrase "average weather" is frequently used to describe climate. The classic era, according to the World Meteorological Organization (WMO), lasts for 30 years. A broader definition of climate includes a statistical description and the current status of the climatic system.

Climate change, as per the World Health Organization, is described as a statistically notable alteration lasting an extended period in either the average state or variability of the climate, usually spanning decades or more. In its report, the Intergovernmental Panel on Climate Change (IPCC) provides a broad definition of climate change "any change in the climate over time whether due to natural variability or as the result of human activity'' [15]. On the other hand, the United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable periods" [15].

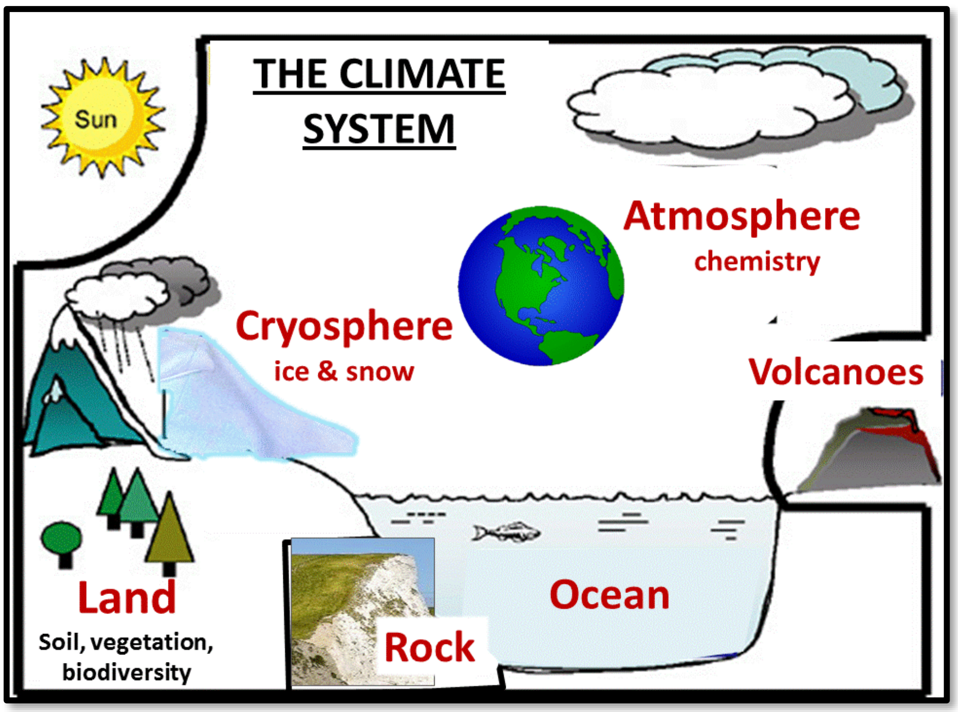


Figure 1. Climate change and its linked systems encompassing the sun, Earth, and oceans [14]

The increase in greenhouse gas levels, deforestation, generation of waste, and population growth are contributing factors to climate change [16,17]. Additionally, massive amounts of chemical pesticides and fertilizers in agricultural fields along with fast industrialization and population growth worldwide, are recognized as significant contributors to climate change [18]. The factors mentioned earlier confirmed the implication of humans through their activities in climate change [19].

However, internal natural processes may also play a role in climate change. Geological records indicate notable shifts in the Earth's temperature caused by various natural phenomena, including fluctuations in solar activity, volcanic emissions, alterations in the Earth's orbit, and concentrations of carbon dioxide (CO_2) [20]. According to Hartter et al., there are two possible causes of climate change: human activity and natural variations [21].

Potential impact of climate change on the life cycle and distribution of plant species: Research has been carried out in Thailand [22], China [23], Indonesia [24], Pakistan [25], and Africa [26-27] to examine how the changing climate is impacting the geographic range of medicinal plants. The distribution and life cycles of the world's vegetation, particularly wild medicinal plants, are being significantly impacted by climate change [28]. Soils and plants are intricately connected due to the fact that plants modify soil characteristics which, in turn, affect plant performance and have a range of interactions (Figure 2). The term “plant-soil feedbacks” (PSFs) describes the effects that plants have on other plant species, themselves, and their progeny as a result of their interactions with abiotic soil conditions and soil organisms [29]. A shifting climate may impact the distribution of plants and their interactions with other soil communities, as climate is a major factor in both organism growth and species distribution [30].

Climate change is therefore anticipated to affect plants and soil organisms in several ways including significant direct effects and indirect effects resulting from changes in the physiological functioning of plants and the composition and volume of resources introduced into the soil. Hence, there could be noteworthy repercussions for PSFs, the vegetation patterns, and the feedback effects influencing local, regional, or even global climate conditions [30]. For example, studies were conducted to assess the implications of global climate change on the regional distribution of *Gentiana rigescens* using the Maximum Entropy Model (MaxEnt) modeling. According to earlier research, this species seems to favor warm and humid climates found in subtropical regions. However, the study done by Shen et al., showed that elevation, annual precipitation, warmest quarter precipitation, temperature seasonality, yearly range, and the mean temperature of the driest quarter all had a significant effect on the likely distribution of *G. rigescens* [31].

In addition, many plant species are predicted to relocate from their native regions to new ones as a result of future climate scenarios. Climate change may help certain species and provide them with a suitable habitat at the expense of others. For instance, the study carried out by Huang et al. on the geographical distribution and effects of climate change on *Glycyrrhiza* species in China revealed that changing climate conditions will increase the suitability of habitats for a few Glycyrrhiza species in the coming years as follows: 61.6% for *Glycyrrhiza inflata*, 47.5% for *Glycyrrhiza squamulosa*, 34.0% for *Glycyrrhiza pallidiflora*, 49.0% for *Glycyrrhiza yunnanensis*, 51.7% for *Glycyrrhiza glabra*, and 65.9% for *Glycyrrhiza aspera* [32]. However, as previously reported by Cahyaningsih et al., eleven Indonesian medicinal plants are anticipated to experience the most restricted distribution areas in the coming years [24]. Additionally, Jayasinghe and Kumar, examined the current and projected distributions of suitable regions for Camellia sinensis (L.) O. Kuntze cultivation in Sri Lanka and predicted a decrease of about 10.5%, 17%, and 8% in the aggregate areas deemed 'optimal,' 'medium,' and 'marginal' suitability, respectively, by the years 2050 and 2070 [33]. This suggests that some species could experience favorable conditions, due to climate change, resulting in a notable decrease in the overall threatened species.

The estimation of climate change’s effect on plant species might be exaggerated due to the chronic neglect of the species or population characteristics and their interactions with the habitat. Although certain species could theoretically acquire new distribution areas (Table 1), various factors, such as altitude [34] and human disturbances in the neighboring region, could hinder their ability to migrate. In the findings of Harnik et al., it is stated that the determination of extinction is impacted by geographic range, habitat breadth, and local abundance [35]. Notably, the rise in extinction levels is projected to occur even when the population of the area is currently abundant due to the loss of geographic range.

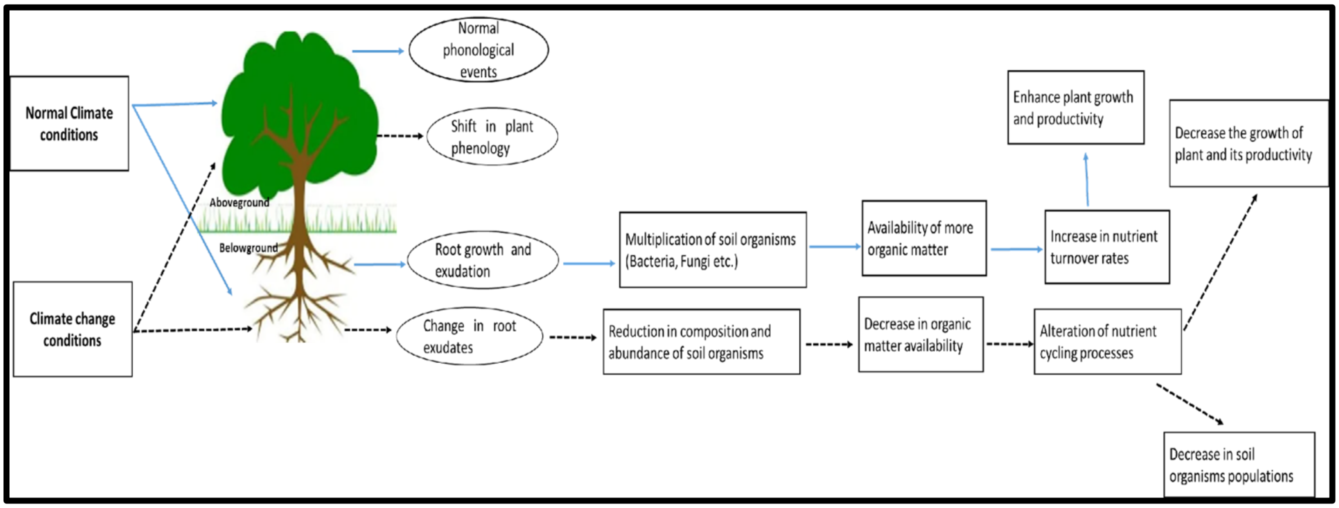


Figure 2. Trophic relationship modifications based on reactions to climate change

Table 1. Climatically suitable areas of the studied species under future climate conditions

Species name	Suitable area under future climate conditions (%)	Set of scenarios used	References
Gentiana rigescens (Franch. ex Hemsl.) Halda	-99.22	RCP 8.5	[31]
Lantana camara L.	+10	RCP 4.5	[36]
Camellia sinensis (L.) O. Kuntze	-10,5	RCPs	[33]
Chromolaena odorata (L.) R.M.King & H.Rob.	+12	RCP 4.5	[36]
Bergenia ciliata (Royle) A.Braun ex Engl.	-12.94	SSP5 8.5	[37]
Podophyllum hexandrum Royle	-74.0	RCP 6.0	[5]
Garcinia indica (Thouars) Choisy	-5.69	RCP 8.5	[38]
Ageratum houstonianum Mill.	+70	RCP 4.5	[36]
Nardostachys jatamansi (D.Don) DC.	+12.45	SSP5 8.5	[37]
Heracleum candicans Wall. ex DC.	-51.3	RCP 6.0	[5]
Aconitum lethale Griff.	-12.94	SSP5 8.5	[37]
Neopicrorhiza scrophulariiflora (Pennell) D.Y.Hong	+26.65	SSP5 8.5	[37]
Rheum acuminatum Hook.f. & Thomson	56	RCP 6.0	[5]
Taxus baccata L.	0	RCP 8.5	[39]
Argania spinosa (L.)	-(32-53)	RCPs	[40]
Ludwigia spp.	−55%	RCP 8.5	[41]
Zea mays L.	-6	RCP 4.5	[42]
Fritillaria cirrhosa D.Don	-83.8	RCP 6.0	[5]
Delphinium himalayae Munz	-63.3	RCP 6.0	[5]
Dioscorea deltoidea Wall. ex Griseb.	68	RCP 6.0	[5]

SPP, shared socioeconomic pathways; RCP, representative concentration pathways

Importance of medicinal plants: Since the dawn of human civilization, the importance of many plant species have been understood for their nutritional, therapeutic, medicinal, and sustenance-giving qualities. Because of their secondary metabolite and pharmacological qualities, medicinal plants are a fundamental important group that are served extensively in the food, cosmetic, pharmaceutical, and medical industries [7]. Throughout history, societies worldwide have harnessed the healing potential of medicinal plants, employing them to address health concerns and combat diseases, even in the face of epidemics. The ancient wisdom surrounding the efficacy of medicinal plants in treating diverse ailments has been prevalent for many years [43].

Herbal plants synthesize a range of secondary metabolites that exhibit various features such as bolstering the immune system contributing to the treatment of different diseases [44]. For instance, earlier research has demonstrated extensive antimicrobial properties of plants including *Zingiber officinale* [45], *Zataria multiflora* [46], and *Helichrysum arenarium* [47]. It has also offered a solution to the challenges posed by antimicrobial resistance developed against antibiotics. When it comes to toxicity or side effects, plant extracts exhibit fewer side effects compared to allopathic medications, potentially reducing the incidence of infections with multidrug resistance due to their pharmacological components [48]. Herbal plant products and medicines, as reported by Gupta et al., are perceived as both safe and economical, resulting in an approximately 80% adoption rate in primary healthcare systems across all regions monitored by the World Health Organization [1,49]. Also, the affordability of herbal medicines renders them as a favorable option for individuals residing in developing nations; however, in recent times, even developed countries have adopted these herbal products. Furthermore, the identification of medicinal plants is restricted, with slightly over half a million species recognized. This suggests a promising outlook for the exploration and study of medicinal plants in the future [1].

Impacts of climate change with respect to medicinal plants: The assessment of the influence of climatic alteration on medicinal plants is conducted through the examination of recent publications, journals, and firsthand observations. Environmental factors significantly affect both the growth of plants and the synthesis of secondary metabolites (SMs). The negative impacts of temperature extremes, salinity, and drought emphasize plant development and productivity. This stems from modifications in metabolic pathways regulating signaling, physiology, and mechanisms of defense. Essential compounds in the interaction of abiotic stresses with plants are plant secondary metabolites, as highlighted by Sharma et al. [50]. After acknowledging the pivotal role of abiotic factors in the growth and development of plants, it is imperative to note that each plant species has specific environmental requirements for its productivity (Figure 3) and optimal growth.

By activating early metabolic reactions, plant cells may restore chemical imbalances necessary for their existence. Plants that can modify their morphology and physiology in response to changes in their surroundings can survive in harsh environments. Therefore, even if a given species' range is unaffected, a changing environment may have a good or negative impact on a medicinal plant’s productivity or quality, specifically its potency or chemical makeup.

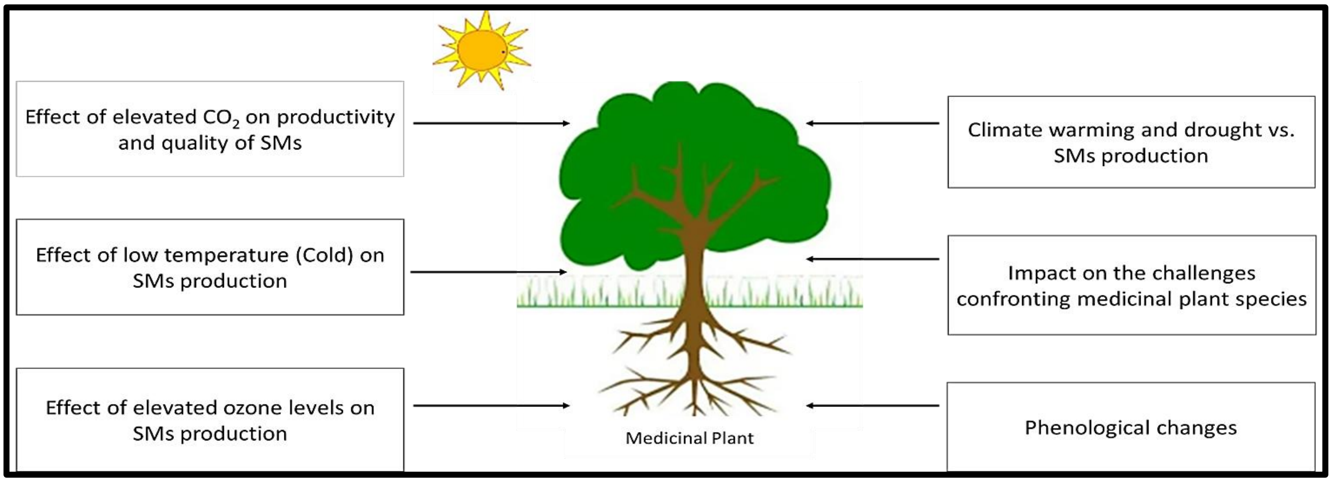


Figure 3. Environmental factors affecting the productivity of secondary metabolites in medicinal plant.

Effect of elevated carbon dioxide (CO_2) on productivity and quality of medicinal plants: Experiments in controlled situations have demonstrated the positive benefits of raised CO_2 on the quality and production of many products and plant-based medicines. Carbon dioxide's concentration has been on a rapid ascent since the Industrial Revolution, escalating from 270 points per million (ppm) to 407.4 ppm [51]. Adapting plants to environmental changes involves metabolic flexibility but this adaptation has consequences for the secondary metabolites which form the foundation of their medicinal properties [52]. As an illustration, *Hypericum perforatum* L., recognized for its efficacy for treating mild depressive symptoms (e.g., mood disorders and anxiety), underwent treatment with augmented levels of CO_2. After 140 days, it exhibited increased growth compared to conditions at ambient CO_2 levels. However, within the identical experiment, there was a marked reduction of 22% in the hypericin concentration under elevated CO_2 conditions (550 ± 50 µmol mol^{-1}). This decrease further intensified to 19.30% when both elevated CO_2 and temperature were concurrently applied [43]. Similarly, with 140 days of CO_2 enrichment, phenological stages (bud and flower production) progressed by four days compared to ambient conditions.

A study on the medicinal plant, *Centella asiatica* (L.) Urb, which offers various therapeutic benefits, revealed enhanced photosynthetic efficiency initially with a larger amount of flavonoids under CO_2 levels at 400 and 800 mol^{-1} [53]. Similar research on *Mentha piperita* L. revealed that the application of heightened CO_2 of 360 ppm and 620 ppm increased the concentration of flavonoids [54]. Likewise, a rise in CO_2 levels resulted in an elevation of the concentrations of various flavonoids and phenolic compounds within the rhizome of ginger (*Zingiber officinale* Roscoe) [55] and artemisinin in sweet Annie (*Artemisia annua* L.) [56]. It has been noted that elevated levels of CO_2 exhibit a favorable influence on both the productivity and quality of diverse products and constituents found in medicinal plants. Cultures of lemon basil (*Ocimum basilicum* L.), peppermint (*Mentha piperita*), and thyme (*Thymus vulgaris* L.) exposed to elevated CO_2 concentrations (3,000 µl/liter of air) exhibited augmented fresh weight, formal leaf, and root numbers, surpassing the growth observed under normal air conditions on the same medium [57]. The general pattern observed in these results emphasizes the relevance of secondary metabolites in medicinal plants concerning CO_2, alongside considerations of seasonal fluctuations, time spans, and nutrient accessibility.

Climate warming and drought versus secondary metabolite production: Numerous investigations have been performed to determine how drought affects the quantity of secondary metabolites present in plants. The results pointed out that in environments experiencing drought stress, plants tend to accumulate higher levels of secondary metabolites, including terpenoids, phenolics, and nitrogen-containing elements such as alkaloids, glucosinolates, and cyanogenic glucosides [1]. Under mild drought stress conditions, *Scutellaria baicalensis* Georgi, a traditional medicinal herb, demonstrates an enhancement in baicalin levels, which, in contrast, decreases under severe stress [58]. This finding supports the notion that a specific level of drought stress could improve the accumulation of baicalin by amplifying the expression and efficacy of essential enzymes responsible for its synthesis. Parallel research conducted by Hosseini et al. investigated *Glycyrrhiza glabra* L. under varying degrees of drought stress, including mild, moderate, and severe conditions [59]. The study demonstrated that drought promoted the formation of glycyrrhizin by enhancing the glycyrrhizin biosynthesis pathway. Nevertheless, under conditions of excessive drought, there was a reduction in the glycyrrhizin content compared to situations with mild and moderate drought [59]. In the findings presented by Alhaithloul et al., it was noted that drought stress results in a decline in the total phenols, flavonoids, and saponin content in both *Mentha piperita* L. and *Catharanthus roseus* (L.) G. Don [60]. Conversely, the concentration of other secondary metabolites (tannins, terpenoids, and alkaloids) rises under stress conditions in both plant species. In summary, studies highlight significant differences in the concentration of secondary metabolites within plants when subjected to varying levels of drought stress.

Impact of cold on secondary metabolites of plants: Stress induced by low temperatures includes chilling stress (occurring between 0 °C and 10 °C) and freezing stress (occurs at temperatures below 0 °C). One of the most severe stresses on plant systems is low temperature, which has various adverse effects on growth, productivity, diversity, and distribution [61]. Additionally, Ruelland et al. found that the physiological aspects of plants are directly impacted by low temperatures [62]. Furthermore, the influence of chilling stress extends to the metabolism of macromolecules and the stability of cell membranes, leading to an inhibition of plants' reproductive development. According to Lianopoulou and Bosabalidis, aromatic or medicinal plants such as *Cistus incanus*, *Teucrium polium*, *Thymus sibthorpii*, *Phlomis fruticose*, and *Satureja thymbra* employ a range of chemical defenses, establish mechanical barriers, and demonstrate seasonal dimorphism to survive cold conditions [63]. Cold stress produces free oxygen radicals which raise internal stress levels and force plant cells to release them by turning on antioxidants [62]. As per Eremina et al., plant cells need to engage numerous enzymatic and metabolic pathways to survive [64]. When seedlings of the fennel plant, *Foeniculum vulgare*, were subjected to 2°C for 2, 3, and 4 hours, they changed chlorophyll content, biomass production, and β-carotene. Conversely, this stress significantly increased antioxidant activity [65]. *Withania somnifera*, popularly known as Indian ginseng, displays a higher withanolide accumulation in its leaves when exposed to low temperatures [66]. Saema et al. reported that transgenic plants of this species exhibit an increase in the metabolite withanolide when exposed to low temperatures [67].

Impact of Ozone (O_3) on Secondary Metabolites of Plants: Although the ozone is acknowledged for protecting against ultraviolet radiation, its effects on plants [77-78] and animals [68] become evident upon reaching ground level. The imposition of increased O_3 levels causing physiological stress in plants may induce the activation of metabolic pathways associated with synthesizing of secondary compounds. For instance, with the stimulation of peroxidase activity by the ozone (110 ppb, 5 hours), *Hypericum perforatum* L. demonstrated an increase in total phenols and flavonoids (quercetin), evidencing that the ozone is an inducer of bioactive secondary metabolites [70]. Likewise, following 24 hours of exposure at 110 ppb, the rise in quercetin was substituted by an elevation in Kaempferol (another flavonol), but isoquercitrin and quercitrin remained unaltered. This demonstrates how O_3 application could increase antioxidant and phytochemical concentrations, hence growing the therapeutic advantages of medicinal plants [51]. In addition, a study conducted by Pellegrini et al., examining the eco-physiological and antioxidant features of *Salvia officinalis* L. under ozone stress (120±13 ppb for a continuous 90-day period) indicated an elevation in phenolic content. Notably, gallic acid increased twofold, caffeic acid increased eightfold, and rosmarinic acid exhibited an augmentation on the 60th day of treatment (+122% compared to control, Figure 4) [71]. Brazilian researchers examined the consequences of extended exposure to ozone on plants of *Capsicum baccatum* L. *var. Pendulum* and they discovered a 50% reduction in capsaicin with a corresponding increase in dihydrocapsaicin in the pericarp [72]. Pant et al. found that when investigating the influence of ozone on plant quality, the available literature extensively covered studies on edible crops [51]. At the same time, there is a scarcity of research explicitly addressing medicinal plants Therefore, further research is required with expansive perspectives and strategies to clarify the influence of this treatment on the generation of secondary metabolites.

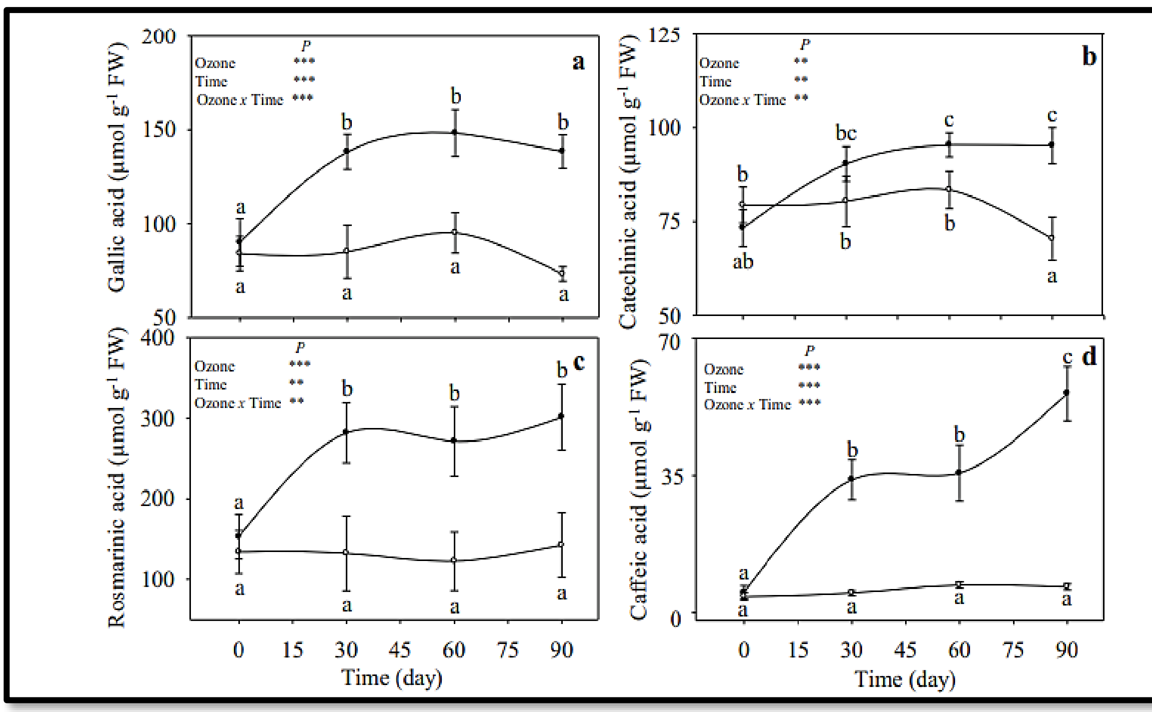


Figure 4. Eco-physiological and antioxidant traits of *Salvia officinalis* L. under ozone stress [71]

Impact on the challenges confronting medicinal plant species: It is widely acknowledged that many plant species are currently at risk of local or global extinction. Recent research reveals that approximately 600 plant species have disappeared over the past 250 years [73]. According to Gafna et al., 14–24% of the anti-malarial plants species available in Kenya will be Critically Endangered (CR), while 14–29% of those species will be Endangered (EN) under all future scenarios [74]. Irrespective of climate change, human activities such as habitat destruction and fragmentation pose a significant threat to wild plant populations worldwide [75]. This leads to the creation of small, isolated populations with an increased risk of local extinction [76]. Other threats encompass the introduction and proliferation of invasive species and exotic pathogens [77]. High-value medicinal plants face increased risk due to unsustainable harvesting requirements. This is illustrated by the case of American ginseng (*Panax quinquefolius* L.), a vital tonic herb used for conditions like fatigue, hypertension, and upper respiratory infections, which is extensively traded in significant amounts to the Chinese market [78]. The species' average stature and abundance has decreased over time, and because of the high demand, there is a considerable issue with unlawful harvesting [78].

In numerous locations, environmental conditions are expected to undergo alterations, reaching a stage where certain species presently inhabiting those areas may no longer endure or prosper [79]. As a result of anticipated climate shifts, the envisaged suitable range for numerous plants species, may either diminish or undergo significant relocations [80]. In contrast, some species may experience expansions in their potential range. According to Lamprecht et al., many organisms are experiencing rapid alterations in their distributions, gravitating towards higher latitudes or elevations, and thereby heightening competition for existing species in those locales [81]. Moreover, changes in phenology may interfere with relationships involving pollinators and other symbiotic organisms in certain species [82]. Insect populations have already been drastically reduced by human actions such as habitat destruction and pollution from pesticides and chemicals [83]. The intensification of climate change is expected to compound this issue further.

Adaptation measures for climate change and global warming: Conservation efforts focused on endangered flora and fauna can diminish the potential vulnerabilities of medicinal plants to climate alteration in the coming years [84]. The establishment of community gardens for cultivating medicinal plants is therefore recommended [79]. In addition, to ensure the adaptation of medicinal plants, it is essential to preserve genetic diversity within natural ecosystems. Policymakers should extend the current protected areas to avoid the depletion of suitable habitats for medicinal plant species [85-86]. Ex-situ conservation is an option to serve as a safeguard against significant losses and to ease the process of reintroduction [74]. Furthermore, the significance of legislation and continuous monitoring cannot be overstated in ensuring the preservation and sustainable exploitation of threatened medicinal plant species [74,84]. The accomplishment of these aims is most likely when initiatives are centered on the conservation of plants within resilient ecosystems. Moreover, it is crucial to investigate and record indigenous traditional knowledge that has the potential to mitigate the effects of climate change [79,84,87]. Studies addressing sustainable harvesting practices are also fundamental [74,79].

Future strategies for research: As a result of overall increasing temperatures (Figure 5) and unpredictable rainfall patterns, climate change is accelerating and its impacts will likely rise in the future.

In the forthcoming research agenda for high-altitude medicinal plants, it is crucial to incorporate the observation of the enduring consequences of the interplay between climate change factors and secondary metabolites in plants [43]. In alignment with observations by other authors, future investigations into the effects of climate change on medicinal plants in high-altitude areas should include: examining reactions of plant ecology and evolution to the latest alterations in climate, scrutinizing the influence of climate change on the concentration and intraspecific variability of diverse secondary metabolites, and assessing extinction risks arising from climate change.

Sharma et al. suggests that climate change could escalate into a more significant issue for the herbal community, posing potential challenges for users, harvesters, and manufacturers of medicinal plant species, as well as their availability as raw material for scientific research [28]. It is now imperative to direct suitable focus towards this category of plants, specifically by recognizing their potential as nutraceuticals. To accomplish this, several investigations should be conducted on various medicinal plant species:

- In contrast to cultivated crops, when dealing with medicinal plants, the strategy should involve examining these crops as well as their characteristics both in their natural environments and cultivated areas.
- A rising potential is present for initiating research to investigate the consequences of climate change on phenological patterns, the movement of species ranges, changes in habitats, and the production of secondary metabolites.
- A pressing requirement exists to set up a global network of Long-Term Ecological Research (LTER) stations in various ecological regions.
- For a complete understanding, further research is necessary in the future regarding the possible effects of increased temperatures, warming, and UV radiation on secondary plant metabolites.
- In the future research agenda for medicinal plants, it is essential to incorporate the observation of prolonged impacts and interactive effects of climate change factors on plant secondary metabolites.
- Developing relevant conservation strategies for endangered medicinal and aromatic plants is a vital task for the future.
- Gathering and documenting indigenous knowledge about the cultivation of medicinal, aromatic, and herbal plants to combat climate change-related factors should be carried out.
- Ensuring the availability of grants for both students and researchers is vital to inspire their examination of climate change adaptation and mitigation approaches. The goal is to protect medicinal plants from the risk of extinction caused by climate change [49]

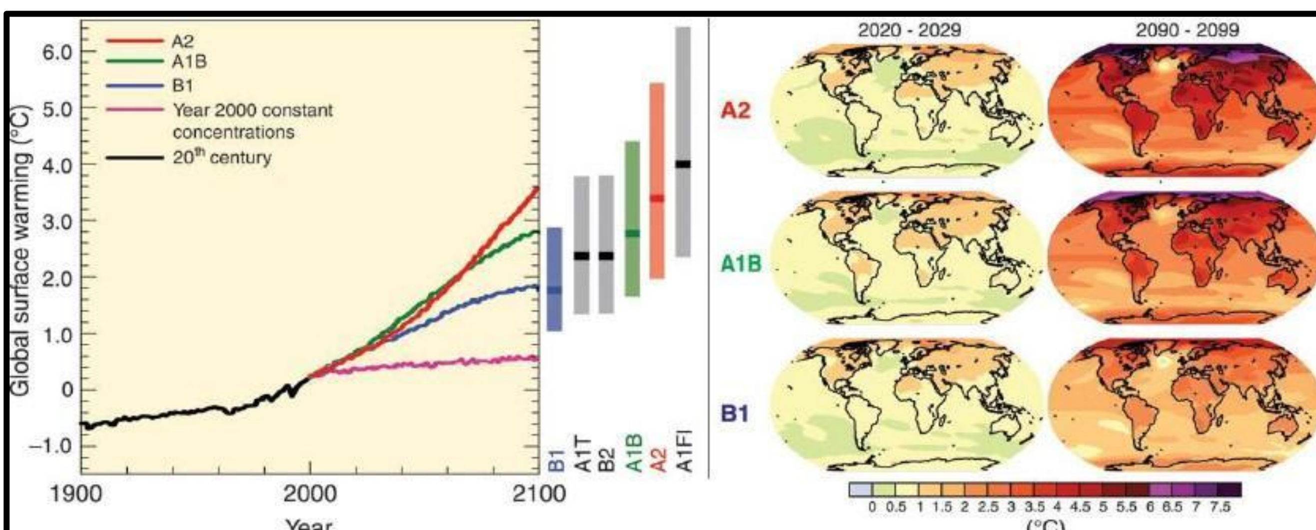


Figure 5. Global average surface temperature change [88]

CONCLUSION AND RECOMMENDATIONS

Plants produce diverse secondary metabolites crucial for daily needs and medicine. However, climate change affects plant physiology, impacting the production of important pharmaceutical compounds. This review emphasizes the effects of rapid climate change on the decline of wild medicinal plant species worldwide. The anticipation is that medicinal plant species will face adverse consequences due to impending climate change, although the specific impact on species distribution and synthesis of secondary metabolites differs among various species. So, by thoroughly examining recent publications and journals, and incorporating personal observations, this review has proposed adaptation measures for climate change and outlined future strategies to ensure the preservation of medicinal plant species for utility and further research. Furthermore, studies on the interactions of various direct and indirect causes of climate variation and their effects on medicinal plants should be thoroughly conducted by future researchers.

List of abbreviations: CO_2, Carbon dioxide; O_3, Ozone; MAPs, Medicinal and Aromatic Plants; WHO, World Health Organization; WMO, World Meteorological Organization; IPCC, Intergovernmental Panel on Climate Change; UNFCCC, Framework Convention on Climate Change; PSFs, Plant-Soil Feedbacks; MaxEnt, Maximum Entropy Model; IUCN, International Union for Conservation of Nature; SPPs, Shared Socioeconomic Pathways; RCPs, Representative Concentration Pathways; CR, Critically Endangered; EN, Endangered; LTER, Long-Term Ecological Research; UV, Ultraviolet

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