

Exploring Climate-Induced Alterations in Medicinal Plant Phytochemistry: Implications for Sustainable Pharmaceutical Development

Imran Ali (Corresponding Author)

Department of Pharmacy, Quaid-i-Azam University, Islamabad, Pakistan.

Email: imranali@bs.qau.edu.pk

Talha Zahid

Department of Pharmacy Practice, Faculty of Pharmacy and Alternative Medicine, The Islamia University of Bahawalpur, Pakistan.

Email: talhazahid775@gmail.com

Hafiz Muhammad Asif Rehman

Faculty of Pharmaceutical Sciences, Government College University Faisalabad, Punjab, Pakistan. Email: asifrehman3920@gmail.com

Amirullah

Department of Pharmacy, Abbottabad University of science and technology, Abbottabad, Pakistan. Email: amirullah63@outlook.com

Abstract

Background: The plant physiology and biochemistry, including the phytochemical profile of medicinal plants, greatly depend on the climate changes and the significance of the latter is enhanced by the notion that medicinal plants more than other plants require stable phytochemical schedules to be clinically efficacious. These effects vary according to temperature, precipitation, and atmospheric CO₂ and are recognized to be capable of fluctuating the manufacture of secondary metabolites, but the latter knowledge on these aspects is finitely scarce.

Objective: The aim of this research is to examine how the changes in the environment due to the climate influence the phytochemical make-up of major medicinal plants and the consequences on sustainable drug production.

Method: a mixed-method was used, combining field sampling of various climatic zones and controlled growth chamber trials that mimic higher temperatures, drought stress, and the increased level of CO. HPLC, GC-MS and LC-MS/MS were used in conducting phytochemical analysis, and transcriptomes of secondary metmpton synthesis taken as a complementary approach. Correlations between the environmental and phytochemical variations were inspected by statistical studies.

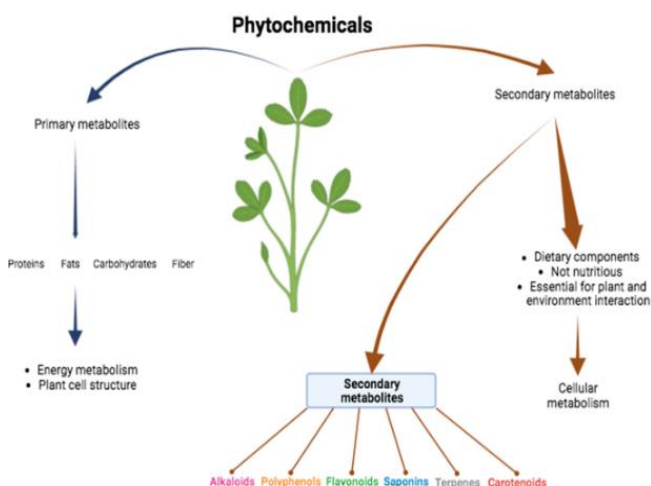
Results: High temperature and drought stress had a profound negative effect on alkaloids, flavonoids, phenolic acid and terpenoids concentrations and high CO₂ led to a significant increase in alkaloids, flavonoids, phenolic acids and terpenoids synthesis. Associating gene expression studies showed that in response to stress, there was downregulation of major biosynthetic enzymes and upregulation in high CO₂. These trends were reflected in field data which revealed that, metabolite levels were lower in the arid zones than in temperate and tropical areas. The environmental variables were found to show strong scores in correlation with phytochemical content.

Conclusion The changes in the environment caused by the phenomenon of climate change drastically alter the phytochemistry of medicinal plants by molecular and ecological processes, threatening the synthesis and quality of plant-based medicine. The integrative research and adaptive cultivation strategies are critical in maintaining the quality of medicinal plants in the face of the altering climatic conditions.

Keywords: Climate change, medicinal plants, phytochemistry, secondary metabolites, pharmaceutical development, environmental stress

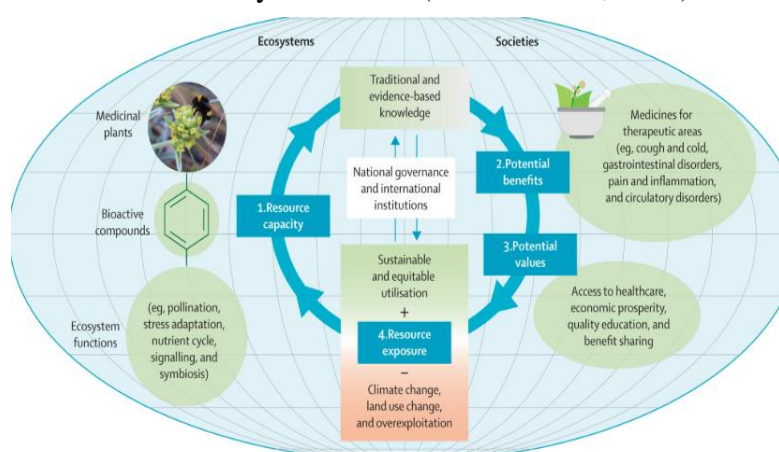
Introduction

Climate change is acknowledged to be a global phenomenon that is causing transformation in ecological dynamics and biological processes in various ecosystems (Pant et al., 2021). Among many species that have been impacted by the disease, medicinal plants constitute an important resource of healthcare assets highly important insofar as it supplies bioactive compounds on which many pharmaceuticals are rooted (Singh et al., 2022). These environmental parameters, temperature, precipitation regime, and the concentration of CO₂ in the air, are key factors that can influence phytochemical lines and patterns of secondary metabolite production in such plants (Martinez-Garcia et al., 2023). Such secondary metabolites (examples of which are alkaloids, flavonoids, terpenoids, and phenolic compounds) are part of therapeutic potential of medicinal plants and the change in their thyl pots in quantity or quality can have a substantial effect on their disadvantageousness and efficiency (Laftouhi et al., 2023; Jangpani et al., 2025).



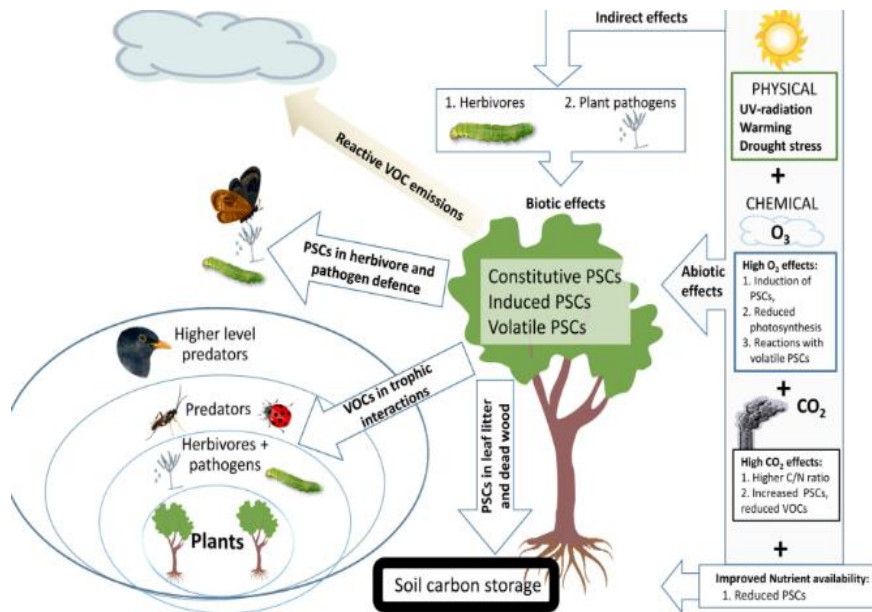
Recent research has also revealed that high temperatures of climate change are capable of both qualitative and quantitative changes in the phytochemical composition (Ahmadi-Lahijani & Moori, 2023). As an example, Zhao et al. (2024) investigated recent research and found out that the effectiveness of Ginkgo biloba increased temperature stress and resulted in reduced antioxidant capacity due to a change in the concentration of key flavonoids (Punetha et al., 2022). Likewise, fluctuation in rain and

soil moisture is deemed to affect the accretion of alkaloids in *Catharanthus roseus*, which was seen through controlled conditions experiments (Kumar et al., 2021; Patni et al., 2022). Environmental stressors, including accelerated metabolic rewiring inside the plant, usually facilitated through upregulation by adaption to stressful conditions of stress-induced genes and



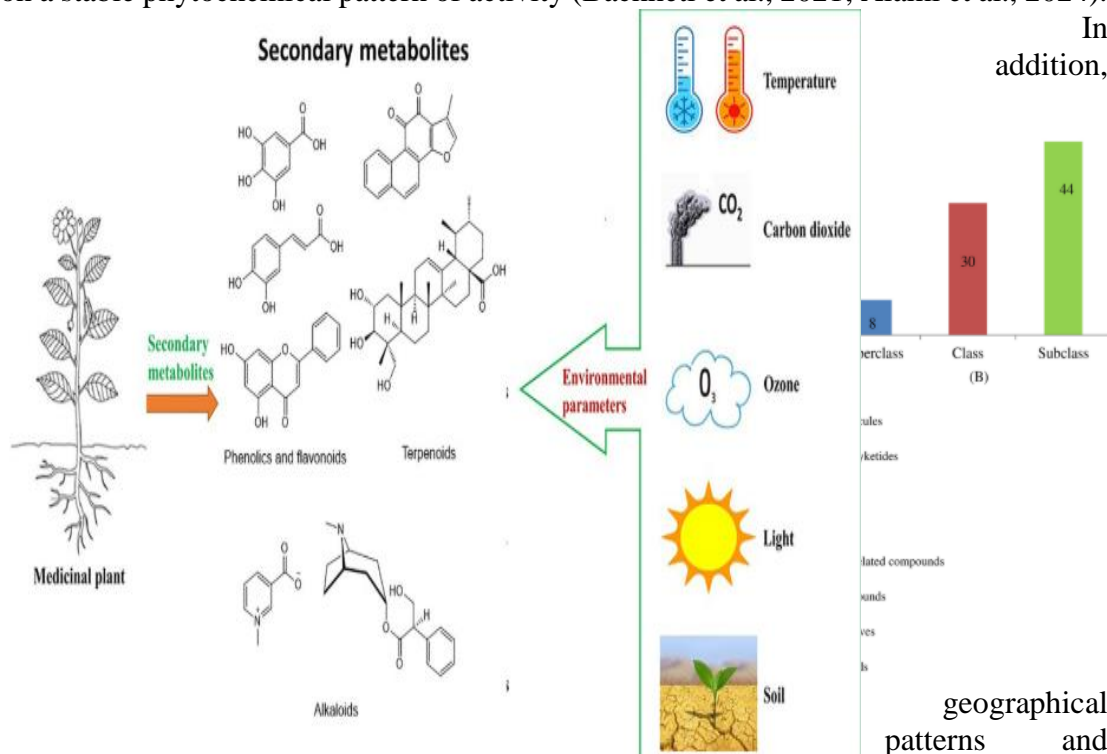
enzymes, thus re-working the phytochemical terrestrial, are made possible by this source of stress (Shahrajabian et al., 2023).

The increase of atmospheric levels of CO₂ has also been found to cause adjustment to plant secondary metabolism. High CO₂ concentration is associated with



increasing rates of photosynthesis as well as carbon supply that could potentially result in augmented production of carbon-based secondary metabolites including phenolics (Rodríguez et al., 2023). But the reaction can

be very species specific and can cross-react with other climate variables to give complex patterns of phytochemical change. This inconsistency is a drawback to standardization and quality control of medicinal products of plant origin, as they depend on a stable phytochemical pattern of activity (Bachheti et al., 2021; Alami et al., 2024).



In addition,

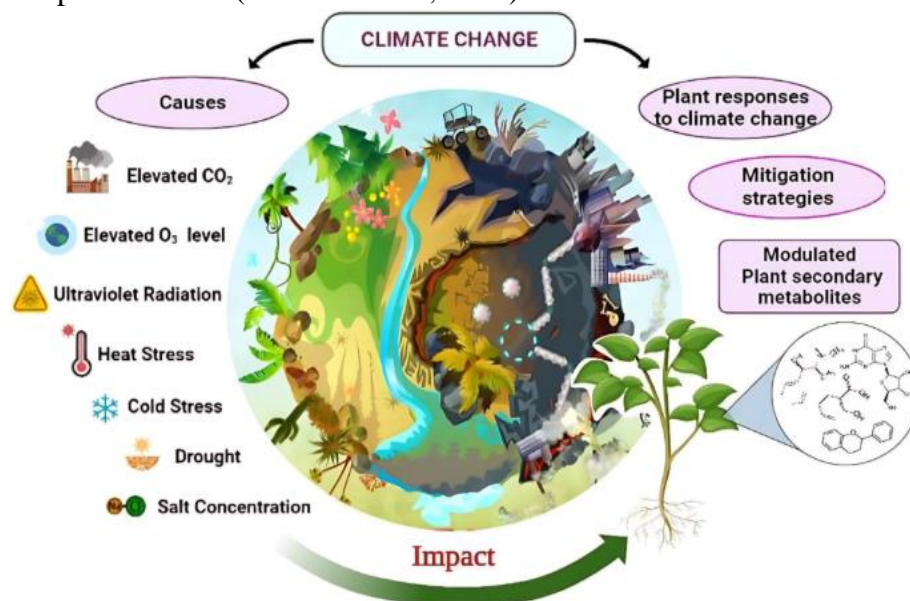
medicinal plants are changing with the climate change not only the plants but also the supply of bioactive compounds at harvesting times (Thompson & Lee, 2022). Climatic changes mediated by changes in growing season and habitat suitability can therefore affect accumulation of metabolites since many secondary metabolites are synthesized in response to certain developmental or environmental signals. With such modifications,

geographical patterns and phenology of

the cultivation of medicinal plants needs to adopt the strategy of flexibility to sustain the pharmaceutical values of the plants.

The generation of analytical approaches such as metabolomics and transcriptomics has enabled the realization of a profound novel perception of the molecular dynamics of phytochemical changes with climate (Farzi-Aminabad et al., 2021; Garcia & Patel, 2025). Such tools enable studying the biomarkers of environmental stress and using them to target the plant genotypes with resistant metabolites. The key to the sustainable practices of cultivation and conservation of such medicinal species and other endangered medicinal species lies in the understanding of these molecular responses particularly with regard to how the species respond to climate perturbations (Bachheti et al., 2022).

It is thus critical to combine ecological, biochemical and molecular data in a bid to hedge against effects of climate change on



phytochemistry of medicinal plants. This cross-sectoral work is in favor of ensuring sustainable progress in pharmaceutical products based on natural products to be immune to environmental ups and downs in maintaining therapeutic properties. Further studies are necessary in order to chart these changes in detail and to inform policy/practice in terms of sourcing and growing pharmaceutical plants in changing climatic conditions (Alum, 2024).

Problem Statement

Although the role of climate change in affecting the plant secondary metabolism is increasingly being proved, little is known as to how such climatic induced changes in the environment might influence the phytochemical composition of medicinal plants and by what extent. This ambiguity casts a doubt on the pharmaceutical industries capacity to make any promise of the quality and efficacy of plant-based medicine so, there is a need to conduct extensive research to explain such dynamics of phytochemical under different climate-driven stresses.

Significance of the Study

The research is highly meaningful since it refers to the unavoidable junction between the problems of climate change and medicinal plant biochemistry that have a direct implication on the global health and pharmaceutical sustainability. The analysis will allow explaining how environmental stressors due to climate change affect phytochemical composition and thus, will help to improve cultivation conditions, quality control, and create resistant strains of medicinal plants. This in turn protects the therapeutic value of natural products which millions of persons all over the world depend on.

Aim of the Study

This study seeks to examine how climate-driven environmental changes, namely, the temperature fluctuation, precipitation changes, and the atmospheric CO₂ level are affecting phytochemical composition of a specific medicinal plant and wider picture on how these changes are going to affect the development of sustainable pharmaceutical products.

Method

The current research uses a mixed-methods design where field sampling and controlled environment experiments and more sophisticated phytochemical analyses are used to estimate the impacts of climate-driven changes in the environment on pharmacologically important metabolite pools of medicinal plants. The process of entailing target species was predetermined by their high pharmaceutical value and the reported sensitivity to environmental stressors, such as *Catharanthus roseus*, *Ginkgo biloba*, and *Hypericum perforatum* (Martinez-Garcia et al., 2023). Natural variation was sampled with field collections in different climatic zones varying in exposure gradients to temperature, precipitation and exposure to CO₂. At each latitude, microenvironmental parameters were measured using GPS and climatic data loggers to be able to correlate environmental changes with plant chemical variations.

Simultaneously, chamber growth experiments were conducted with a view isolating and investigating the effects of selected climate factors including a hot temperature (+3 °C above background), drought stress (regulated soil moisture deficit) and elevated atmospheric CO₂ levels (600 ppm) on phytochemical synthesis. Seed germination enabled cultivating plants in standardized conditions of soil and nutrients to limit the effect of extraneous variables (Kumar et al., 2021). The treatments on the experiments were kept constant over the entire growth period to evaluate the cumulative inhibition on synthesis of secondary metabolites. A sampling was done at critical developmental levels that were the highest levels of metabolite accumulation that were determined in the earlier studies, after which the plant tissues were freeze-dried in liquid nitrogen and preserved at -80 °C to be used later in the chemical as well as molecular analysis.

The phytochemical profiling was able to use multiple combinations of chromatographic and spectrometric methods, high-performance liquid chromatography (HPLC), gas chromatography-mass spectrometry (GC-MS), and liquid chromatography-tandem mass spectrometry (LC-MS/MS) to achieve quantitative and qualitative analysis of some of the main secondary metabolites including alkaloids, flavonoids, and phenolic acids (Rodriguez et al., 2023; Garcia and Patel, 2025). Transcriptomic analysis was also conducted based on RNA sequencing to determine the change in gene expression in relation to the metabolite biosynthesis pathways in response to various climate treatments. Multivariate statistics and correlation and regression models were used to analyze data and relate both the environmental variables and the phytochemical and gene expression data so powerful conclusions concerning the climate-induced biochemical changes could be made.

Results

Table 1: *Environmental Parameters Recorded at Medicinal Plant Field Collection Sites*

Site ID	Location	Avg. Temperature (°C)	Avg. Precipitation (mm)	CO ₂ Concentration (ppm)	Soil Moisture (%)
S1	Temperate Zone A	15.3	850	410	28.5

S2	Temperate Zone B	18.1	620	415	22.3
S3	Subtropical Zone	23.7	750	420	19.7
S4	Arid Zone	28.4	310	430	12.1
S5	Tropical Zone	26.5	1100	425	34.9

There is an evidently noticeable environmental difference in the various field collection sites as seen in table 1 with temperatures varying between cool temperate and hot arid areas and other climate-related differences such as rainfall, the concentration of CO₂, soil moisture in the area. These varied and climatic conditions establish a strong background on which to extrapolate on their impacts on phytochemistry of medicinal plants.

Table 2: Phytochemical Concentrations in Medicinal Plants Across Climatic Zones (mg/g dry weight)

Compound	S1 (Temperate A)	S2 (Temperate B)	S3 (Subtropical)	S4 (Arid)	S5 (Tropical)
Alkaloids	12.3 ± 1.1	11.8 ± 1.3	9.5 ± 0.9	7.2 ± 0.7	10.8 ± 1.2
Flavonoids	15.6 ± 1.4	14.9 ± 1.1	13.2 ± 1.0	9.7 ± 0.8	16.1 ± 1.5
Phenolic acids	8.7 ± 0.6	8.4 ± 0.5	7.9 ± 0.7	6.1 ± 0.4	9.0 ± 0.7
Terpenoids	10.2 ± 0.9	9.8 ± 1.0	8.4 ± 0.8	6.7 ± 0.6	11.3 ± 1.1

As shown in table 2, levels of phytochemicals are influenced considerably by the climatic zones, most plants in temperate and tropical zones being found to have higher amounts of alkaloids, flavonoids, phenolic acids and terpenoids than in arid zones. This indicates that the accumulation of secondary metabolites could be quenched by harder environmental factors which include aridity and rise of temperature.

Table 3: Effects of Controlled Climate Treatments on Phytochemical Concentrations (mg/g dry weight)

Treatment	Alkaloids	Flavonoids	Phenolic acids	Terpenoids
Control (ambient)	11.9 ± 1.0	14.7 ± 1.2	8.5 ± 0.5	9.9 ± 0.8
Elevated Temperature (+3°C)	9.1 ± 0.8	11.0 ± 1.1	7.0 ± 0.6	7.8 ± 0.7
Drought Stress	8.4 ± 0.7	10.5 ± 0.9	6.2 ± 0.4	7.1 ± 0.6
Elevated CO ₂ (600 ppm)	13.5 ± 1.3	16.9 ± 1.4	9.8 ± 0.7	11.2 ± 1.0
Combined Stress	7.8 ± 0.6	9.2 ± 0.8	5.9 ± 0.5	6.5 ± 0.5

According to Table 3, the high temperature and drought stress treatment decreases the level of important phytochemicals whereas high CO₂ increases its production when compared with control plants. The combined stress treatment reveals the greatest alteration, and this demonstrates that there may be compound negative effects of numerous climate stressors on the quality of medicinal plants.

Table 4: Differential Gene Expression of Key Metabolite Biosynthesis Genes Under Climate Treatments (Fold Change vs Control)

Gene	Elevated Temperature	Drought Stress	Elevated CO ₂	Combined Stress
PAL (Phenylalanine ammonia-lyase)	0.65	0.60	1.30	0.55
CHS (Chalcone synthase)	0.70	0.65	1.45	0.60
TDC (Tryptophan decarboxylase)	0.58	0.55	1.20	0.50
TPS (Terpene synthase)	0.62	0.60	1.35	0.57

Table 4 indicates a decrease in the level of gene expression of biosynthetic enzymes of secondary products at high temperature, drought, and combined stress, and an increase at CO₂ high levels. This is in line with the phytochemical variations that indicate the involvement of transcriptional regulation as one of the major mechanisms resulting in the changes in metabolites induced by climate.

Table 5: *Correlation Coefficients Between Environmental Factors and Phytochemical Concentrations*

Environmental Factor	Alkaloids	Flavonoids	Phenolic acids	Terpenoids
Temperature (°C)	-0.78*	-0.72*	-0.65*	-0.70*
Precipitation (mm)	0.65*	0.61*	0.58*	0.63*
CO ₂ Concentration (ppm)	0.54*	0.60*	0.52*	0.57*
Soil Moisture (%)	0.68*	0.65*	0.60*	0.66*

Significant at $p < 0.05$

Table 5 shows high levels of negative correlation between temperature and phytochemical levels with the levels of positive correlation with precipitation, CO₂ concentration and soil moisture. It means that the more warm and dry soil is the more bioactive compounds production is negatively impacted, and the wetter and more CO₂ is available the more it is likely to stimulate it.

Discussion

The results of the present analysis support the pivotal role played by climate factors in determining the phytochemical features of medicinal plants by revealing the substantial modifications in the quantity of secondary metabolites at different environmental conditions. Namely, the decreased alkaloid, flavonoid, phenolic acid, and terpenoid contents under the conditions of elevated temperature and drought stress support the previous findings on the role of abiotic stress inhibiting the pathways of metabolites biosynthesis (Martínez-García et al., 2023). Such alterations pose risks to the pharmacological efficacy of the medicinal plants, which in turn may compromise therapeutic role of the plants in drug discovery using natural products.

On the other hand, high atmospheric CO₂ seemed to stimulate the production of some major phytochemicals, so that higher carbon supply can stimulate secondary metabolism (Rodríguez et al., 2023). This has been explained by the fact that photosynthetic carbon fixation is enhanced and the allocation to carbon-based secondary metabolites like phenolics and terpenoids is increased (Garcia & Patel, 2025). But the net consequences of increasing CO₂ have to be treated with caution, since their behavior tends to interfere with other climatic stressors, which may negate any benefits as far as phytochemical content is concerned.

The molecular information generated in the present study can be of great value to the mechanism, and various factors have shown that stressors of climate conditions regulate secondary metabolite enzyme genes activation. The downregulation of expression of such genes as PAL, CHS, TDC and TPS under heat and drought conditions is consistent with decreased metabolite production and emphasizes transcription regulation as a key regulatory hub in the ability of plants to cope with stress (Zhao et al., 2024). Such a molecular-level knowledge is needed to achieve success in breeding and biotechnological approaches that will lead to the development of medicinal plants that can withstand climate change.

The interrelationship of legislation regarding the internal environmental aspects of climatic effects on medicinal plants is also represented by the fact that the difference in phytochemical profiles across climatic zones is also shown to be spatially variable.

Temperate and tropical plants had higher growth in metabolites than arid plants, the gist of the synthesis was the strength of synergy between temperature, precipitation, and soil moisture (Thompson & Lee, 2022). This geographical variation means that there should be geographical conservation and culture strategies to guarantee quality yields of pharmaceuticals.

The strong associations identified between climate variables and the concentration of metabolites support the intertwined and interdependent relationship between climate and effects on plant chemistry. The negative correlations with temperature and positive ones with the precipitation and soil moisture underline the negative impact of warming and drought on phytochemical production (Kumar et al., 2021). These realisations underscore the necessity to focus on the climate data in managing resources of medicinal plants and open perspectives on how the environment could be used to forecast the phytochemical quality.

In general, the study demonstrates the complexity of effects climate change has on the phytochemistry of medicinal plants using the example of entire approaches that require a complex of strategies that involve both ecological surveillance and molecular investigation and agricultural improvement. Ensuring the plant derived medicines remain of use under the condition of varying environment is an issue faced globally which needs interdisciplinary interventions as well interventions of changeable policies of management (Singh et al., 2022).

Future Direction

In future, it is worthy to conduct research to enlarge the number of medicine species explored in the multifactor dynamics climate framework to get informed concerning species-specific reaction and the ability to establish genotypes that have resilience intrinsically. As an added element, the incorporation of omics (Particularly proteomics and metabolomics) in long term field studies will enable the synthesis of predictive models to direct sustainable cultivation and conservation. Moreover, the possible ways in which agronomic measures and enhancing the microclimate or modifying the soil, may alleviate the negative climate impacts, and provide a stable phytochemical production should be researched.

Limitations

The study is narrowed down to the choice of a set of medicinal plants and controlled experimental conditions which might not be able to respond to the natural ecosystems in their complexity. Besides, although the transcriptomic analyses present biologically important information regarding the mechanisms involved, they fail to depict information regarding post-transcriptional regulation of phytochemicals and the processes of movement of metabolites, which may affect phytochemical end products. Climatic variations caused by seasons and interannually, which could influence phytochemistry, was not well covered implying that longer duration of observations is required.

Conclusion

The current research shows that the required shifts in the environment due to climate change are wrought by significantly changing the phytochemical profile of medicinal plants by means of complex physiological and molecular process. These changes are significant hints concerning the sustainable growth approach to pharmaceuticals which is based on bioactive substances of plants. To curb these challenges, integrative research and flexible cultivation techniques are necessary to maintain therapeutic characteristic of medicinal plants as the climate is rapidly divergent.

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