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A Concise Review on Ultraviolet Radiation and Its Potential to Enhance the Pharmacological Profile of Medicinal Plants via Secondary Metabolite Production

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A B S T R A C T

Objective: Ultraviolet (UV) radiation, a component of the solar electromagnetic spectrum, functions both as an environmental stressor and a biological stimulus. Medicinal plants exposed to UV particularly UV-B and UV-C wavelengths often show enhanced synthesis of secondary metabolites, including flavonoids, phenolic compounds, alkaloids, and terpenoids. These metabolites are well recognized for their antioxidant, anti-inflammatory, anticancer, and antibacterial properties. This review aims to examine the effects of different UV wavelengths and doses on the chemical composition and therapeutic potential of medicinal plants.

Methodology: A comprehensive literature survey from 2000 to 2025 was conducted, covering diverse plant species and genotypes exposed to UVA, UVB, or UVC radiation, alone or in combination with environmental factors such as drought stress or hormonal treatments. Key parameters analyzed included growth characteristics, photosynthetic activity, phenolic and antioxidant content, and alkaloid production.

Results: Controlled UV exposure was found to significantly enhance secondary metabolite accumulation, increase antioxidant activity, and improve the pharmacological properties of medicinal plants. In contrast, excessive UV exposure could impair growth and induce cellular damage. The combination of UV with hormonal treatments or salicylic acid frequently upregulated gene expression in metabolic pathways associated with bioactive compound synthesis. The intensity, duration, and wavelength of UV radiation were critical determinants of chemical composition and biological activity.

Conclusion: Appropriately timed and dosed UV radiation represents a promising strategy to augment secondary metabolite production and enhance the therapeutic value of medicinal plants. These findings have important implications for optimizing cultivation practices and developing effective plant-based pharmaceuticals.

Keywords: Ultraviolet (UV) radiation, medicinal plants, secondary metabolites, flavonoids, phenolic compounds, antioxidants, alkaloids

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Introduction

Ultraviolet (UV) radiation, a component of the solar electromagnetic spectrum with wavelengths ranging from 100 to 400 nm, is conventionally divided into three regions: UVA, UVB, and UVC [1]. UV radiation is recognized both as an environmental stressor and as a biological stimulus [2]. In response to UV exposure particularly UVB medicinal plants often enhance the production of secondary metabolites, including flavonoids, phenolic compounds, alkaloids, and terpenoids [3]. These bioactive compounds are of considerable therapeutic importance due to their antioxidant, anti-inflammatory, anticancer, and antibacterial properties [3]. However, UV radiation is a double-edged sword: excessive exposure can damage DNA, proteins, and cellular membranes, whereas controlled and moderate exposure not only avoids harmful effects but can also improve the quality and therapeutic efficacy of medicinal plants [4]. Medicinal plants represent valuable sources of bioactive compounds with proven therapeutic effects [4,5]. Yet, the concentration and quality of these metabolites are highly influenced by environmental factors, with UV radiation playing a particularly prominent role [4,5]. In recent years, there has been growing interest in elucidating how UV exposure modulates secondary metabolite pathways. Such knowledge is pivotal for optimizing medicinal plant cultivation and developing innovative strategies to enhance their pharmacological potential [4,5]. The present study aims to review the effects of different UV wavelengths and doses on the chemical composition and therapeutic value of medicinal plants.

Methodology

A comprehensive literature survey was conducted, covering publications from 2000 to 2025. The studies included diverse plant species and genotypes exposed to UVA, UVB, and UVC, either alone or in combination with environmental stressors or hormonal treatments. Key parameters analyzed were plant growth, photosynthetic activity, and levels of phenolic compounds, flavonoids, and alkaloids. The collected data were synthesized to evaluate the overall impact of UV radiation on secondary metabolite accumulation and the therapeutic potential of medicinal plants. Databases used for article searching included PubMed, Scopus, Web of Science, ISC, SID, and Google Scholar.

Results

Evidence from multiple studies indicates that controlled UV exposure can significantly enhance the production of secondary metabolites and improve antioxidant and therapeutic activities in medicinal plants. In species such as basil, tomato, mallow, artichoke, purslane, thyme, and Catharanthus roseus, UV treatment was associated with increased levels of flavonoids, phenolics, anthocyanins, and alkaloids. Conversely, excessive exposure or short-term irradiation in some species negatively affected early growth and photosynthetic performance. Furthermore, the combination of UV with environmental factors or hormonal treatments positively influenced gene expression and secondary metabolite production, highlighting the potential of UV as a strategic tool to enhance the pharmacological value of medicinal plants. Detailed information on these findings is summarized in Table 1.

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Table 1: Effects of UV Radiation and Environmental Stresses on Growth, Photosynthetic Compounds, and Secondary Metabolites in Medicinal and Beneficial Plants

Year	Plant / Cultivar	Type of UV / Stress	Effect on Photosynthetic Compounds	Effect on Phenolic and Antioxidant Compounds	Key Findings	Ref.
2000	Basil	UV at flowering stage, in vitro	–	Enhanced antimicrobial activity of essential oils	UV exposure significantly boosted antimicrobial activity of volatile oils	[6]
2001	Mentha arvensis L. var. piperascens	UV, 8 and 20 W treatments	–	Piperitenone decreased, Piperitenone oxide increased	UV altered the chemical composition of essential oils, affecting bioactive compound balance	[7]
2006	Hyoscyamus	UV-B and UV-C	Reducing sugars in roots and leaves	Flavonoids and anthocyanins increased by 35–50%	UV induced a shift from primary to secondary metabolite accumulation	[8]
2010	Tomato	UV-B, 2 and 4 h treatments	–	Increased antioxidant compounds; phenylalanine ammonia-lyase (PAL) and protein activity varied	UV-B enhanced antioxidant content in ripe fruits, potentially improving nutritional quality	[9]
2013	Mallow	UV-B and UV-C	–	Apigenin and delphinidin increased; lipid peroxidation increased	UV effects on flavonoids and anthocyanins were variable at cellular level, indicating stress-specific responses	[10]
2014	Lemon balm	UV-B and UV-C	Reduced fresh and dry weight, decreased stem elongation	Increased antioxidant enzyme activity and PAL activity	Salicylic acid treatment mitigated UV-induced growth inhibition and oxidative stress	[11]
2016	Artichoke / multiple genotypes	UV-A, 4 h/day	Reduced chlorophyll a, b, and total chlorophyll	Total phenolics, flavonoids, and antioxidant capacity increased	UV-A exposure enhanced phenolic and antioxidant compounds despite reduced photosynthetic pigments	[12]
2017	Satureja montana / Plant calli	UV	–	Flavonoids decreased, phenolics increased	UV effectively stimulated secondary metabolite and antioxidant production in undifferentiated tissues	[13]

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2018	Wheat / Mihan & Pishgam	UV + drought stress	–	Flavonoids increased in Mihan but decreased in Pishgam; anthocyanins increased	Combined UV and drought induced oxidative stress and modulated enzyme activity differently across cultivars	[14]
2019	Satureja montana	UV-A and UV-C	Photosynthetic pigments decreased over time; carotenoids +42%	Total flavonoids increased ~50%	UV enhanced artemisinin and essential oil compounds despite partial photosynthetic pigment loss	[15]
2020	St. John's Wort	Natural UV, 2110 m altitude	–	Increased phenolics and flavonoids	Natural high-altitude UV exposure improved accumulation of beneficial biochemical compounds	[16]
2020	Purslane	UV-B, UV-A, UV-C (60 min)	–	Increased productivity and antioxidant activity	Controlled UV application is a viable strategy to enhance purslane yield and bioactive content	[17]
2021	Hyoscyamus niger / root hair	UV-B	Reduced root hair weight	Increased atropine content and antioxidant enzyme activity	UV-B was most effective in stimulating alkaloid production in root hairs	[18]
2022	Geranium	High-intensity UV-B	Reduced chlorophyll a & b; carotenoids increased	Total phenolics, flavonoids, anthocyanins, and antioxidant activity increased	High UV-B intensity selectively boosted antioxidant compound accumulation	[19]
2022	Thyme	UV + Hormone	–	Metabolites increased after 24 h; decreased after sucrose activation	Synergistic hormone-UV signaling initially enhanced metabolite production	[20]
2022	Purslane	UV-C, various doses	Reduced chlorophyll a, b, and carotenoids vs. control	Increased phenolics, flavonoids, antioxidants	Controlled UV-C effectively enhanced productivity and secondary metabolites	[21]
2022	Thyme	UV-B + Salicylic acid	–	Upregulated DXR, GTS, CYP178, CYP180 gene expression	Combined UV-B and salicylic acid treatment maximized gene expression and metabolite accumulation	[22]
2023	Soybean	UV-B and UV-C, 1–4 h (~9000 J m^{-2})	Reduced shoot length and dry weight; root length reduced	–	Short-term UV exposure reduced germination and early seedling growth, negatively affecting plant establishment	[23]

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2024	Catharanthus roseus (‘Sunstorm Apricot’, ‘Cora-Red’, ‘Cora-XDR Polka Dot’)	UV-A (365 nm) & UV-C (250 nm), 10.8 kJ m^{-2}/day in last 5 of 35 days	UV-C: total dry mass −59%, leaf area −75%, photosynthesis rate −80%; UV-A growth near control	UV-C increased anticancer alkaloids up to 125%	UV-C strongly reduced biomass but enhanced alkaloid production; UV-A had minor growth effects	[24]
2025	Pepper (Çermik, Kandil, Üçburun)	Gamma rays (0–500 Gy) & UV (0.5–1 m, 1–2 h)	Reduced root collar diameter, root length, fresh and dry weight, leaf color (L, a, b)	Changes in protein and proline content	UV and gamma treatments reduced early growth; UV had stronger effect on genetic variability; 200–300 Gy and 0.5 m UV most effective	[25]

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Discussion

A review of the literature indicates that controlled UV exposure plays a crucial role in modulating secondary metabolite production in medicinal plants. These effects are influenced not only by the wavelength and intensity of UV but also by the duration of exposure and species-specific responses [26]. In certain species, UV-B and UV-C irradiation significantly increased flavonoids, phenolics, anthocyanins, and alkaloids, accompanied by enhanced antioxidant activity and overall therapeutic potential [27]. These findings suggest that plants can actively regulate their defense mechanisms in response to UV, producing bioactive metabolites that act as natural protective agents against environmental stressors [28]. However, excessive or prolonged UV exposure can have detrimental effects, such as reduced growth, chlorophyll content, and dry biomass in some species [29]. Therefore, careful management of UV parameters—including wavelength, intensity, and duration—is essential to maximize benefits while minimizing negative impacts [30]. Moreover, combining UV treatment with hormonal applications or salicylic acid positively influenced gene expression in secondary metabolite pathways, indicating that interactions between external and internal signaling can optimize the pharmacological potential of medicinal plants [31]. Controlled and strategic application of ultraviolet (UV) radiation offers a promising approach to enhance the pharmacological profile of medicinal plants. Among UV types, UV-B and UV-C are the most effective in stimulating secondary metabolite accumulation, whereas UV-A generally exerts milder effects on growth and metabolite production. Short-term, carefully controlled exposure is recommended, as prolonged UV treatment can negatively impact biomass and photosynthetic efficiency. Moreover, combining UV exposure with hormonal treatments (e.g., methyl jasmonate) or salicylic acid can synergistically upregulate genes in secondary metabolite pathways, optimizing the synthesis of bioactive compounds. It is important to note that responses to UV vary across species and cultivars, so optimization should be tailored to the specific plant type. Additionally, integration of UV treatment with other environmental factors, such as drought or nutrient stress, requires careful monitoring to prevent excessive stress that may counteract beneficial effects. In summary, precise and well-managed UV application, considering wavelength, intensity, duration, species, and environmental conditions, can effectively improve secondary metabolite production and the therapeutic potential of medicinal plants. Future research should aim to establish species-specific UV protocols to provide clear, evidence-based guidelines for practical application. The bioactive compounds and secondary metabolites of medicinal plants play a key role in their therapeutic and biological activities. These molecules can enhance immune function and antioxidant capacity, contributing to the prevention and improvement of various disorders and diseases [32-37].

Conclusion

The findings of this review highlight that strategic and controlled UV exposure can serve as an effective tool to enhance the medicinal value of plants. Given the critical role of secondary metabolites in biological and therapeutic activities, applying UV in a regulated manner—particularly in greenhouse or controlled-environment cultivation—offers a promising strategy to increase the concentration of bioactive compounds and improve the therapeutic value of plant-derived products. This review also emphasizes that the design of UV application programs must carefully consider species, genotype, and environmental conditions to maximize beneficial effects while minimizing potential negative outcomes.

Statements and Declarations

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Competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

Ethics approval

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ES and RL: Conceptualization, original draft writing, investigation, formal analysis, and manuscript review and editing.

Author contributions

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