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Physiological Regulation of Plants for Enhanced Bioactivity

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Abstract

Plant secondary metabolites, such as terpenoids, phenolics and alkaloids, play a significant role in plant defence and have a wide range of pharmacological and industrial applications. However, the utility of their use is limited by the complex environmental and physiological dependencies which lead to different and low yields. This systematic review offers a thorough review of strategies used to manipulate plant physiology with the ultimate effort of reducing the fundamental yield-quality paradox and improving the biosynthesis of secondary metabolites. The review first outlines how a plant's innate stress response is creatively tapped. Physiological elicitors, such as natural stressors (water deficit, light quality and temperature extremes), act as natural stressors, causing oxidative stress, and diverting carbon flux towards defense pathways. On this, specific abiotic and biotic elicitors (e.g., Jasmonates, Chitosan) and fine tuning of the nutrition modulation are studied and their efficacy in achieving hyper-accumulation of controlled secondary metabolites is examined. Two important transitions are underscored: an approach to genome editing for proactive metabolic pathway manipulation using CRISPR/Cas9, and the incorporation of multi-omics data to understand the complex regulatory networks. Though there are some issues of economic scalability and complicated ethical / regulatory issues to overcome, the future of the field is a closed loop system that combines these cutting edge technologies. This will likely lead to the development of predictive models for designing biofortified crops, global health advances and establishing the future supply of high-value compounds.

Introduction

1 Plant Secondary Metabolites and Bioactivity

Secondary metabolites are low molecular weight organic compounds that do not play an active role in the main metabolic functions of the plant (growth, development and reproduction). Rather, they play important ecological roles, as a chemical defense against herbivores and pathogens, attracting pollinators and seed dispersers and assisting plants to adapt to their environment (Ahlawat et al., 2024). This intrinsic biological role creates an intriguing duality, as the same compounds that serve as beneficial chemical defense mechanisms in plants are now acknowledged for their significant pharmacological, nutraceutical, and industrial significance in humans (Bolat et al., 2024). An evolutionary rework: humans have learnt to

change and harvest these compounds for their benefit, but not their intended purpose.

Plant secondary metabolites consist of terpenoids, phenolics and alkaloids, and they are present in thousands of variants each that are biosynthesized in a different manner. Terpenoids, for instance, account for a large amount of these metabolites, which can be synthesized from acetate through the mevalonic acid pathway (MAP) with about 23,000 structural variants (Kumar & Kumar, 2024). Another large group of phenolics, which includes more than 8,000 identified compounds, are flavonoids and polyphenols, and are biosynthesized via the Shikimic acid pathway (Kumar & Kumar, 2024). This enormous chemical diversity offers a wealth of potential for the creation of new drugs, functional foods, and other valuable products (Sreenivasulu & Fernie, 2022).

The Foundational Role of Physiological Regulation

Their valuable bio-formulations are synthesized naturally and are very dependent on the environment, physiology and genetics, which is very low in quantity (Fazili et al., 2022). Traditional approaches to agriculture can be problematic because of seasonal and geographical fluctuations that can lead to inconsistent yields and concentrations of compounds (Fazili et al., 2022). The field has now moved to the physiological control of plants to overcome these constraints. This method of stressing the plants involves triggering a desired level of stress which further triggers the plant's natural defence system and shifts metabolic flow towards the production of the desired compounds (Jan et al., 2021).

The purpose of this systematic review is to give an overview of the current status of research in this field of transformation. It will systematically discuss how natural as well as targeted interventions can be used to manipulate the physiology of plants for improving their bioactivity. This review brings together a disjointed set of knowledge from across the disciplines of environmental sciences, plant biochemistry and state of the art biotechnology, and correlates the information into a coherent, meaningful story. The vision is to describe the state of the art, but also to determine the key challenges and offer a vision for the future of this fast-moving subject area.

2 The Biomechanical and Metabolic Foundations of Plant Bioactivity

Major Biosynthetic Pathways

Numerous plant secondary metabolites are derived from a few key metabolic pathways. The variety of these types of compounds demonstrates the plant's complex biochemical processes. The mevalonic acid pathway is a key source of biologically active compounds in plant and its terpenoids begin with acetate (Stephane 2020). The Shikimic acid pathway, also referred to as the phenylpropanoid pathway, is the pathway by which phenolics are synthesized and comprises more than 8,000 components (Upadhyay et al., 2025). This pathway is also important as it is a crucial link between primary and secondary metabolism, since aromatic amino acids are also the key products in plant's primary metabolic functions (Wu et al., 2022).

Secondary Metabolites as Regulators of Plant Growth and Defense

Secondary metabolites of plants are not only defence molecules, but also active regulators of plant physiology and growth. They are important for altering a plant's signaling network, especially when it is attacked by herbivores or pathogens (Erb & Kliebenstein, 2020). For instance, some of the products of glucosinolate hydrolysis have been used to test in the root meristems of the plant Arabidopsis and have been shown to inhibit their growth by interfering with auxin signaling (Urbancsok et al., 2017). Other glucosinolate catabolites also play a role in the stomatal closure mechanism, which is an essential function in drought tolerance (Hossain et al., 2013). This suggests a complex layer of self-regulatory metabolism in

which secondary metabolites, after their synthesis, may interact with the plant's physiological and metabolic processes to modulate its response to the environment.

The Interplay between Primary and Secondary Metabolism

Secondary metabolite biosynthesis is tightly coupled to primary metabolism, including essential processes like photosynthesis, respiration, sugar and amino acid biosynthesis (Toscano et al., 2019). The carbon skeletons of primary and secondary compounds are provided through the Shikimic acid pathway, for example (Shende et al., 2024). Under stress, a plant may decrease its investment in primary metabolism to invest the resources in the production of secondary metabolites that are involved in defense. This is one of the compromises made: The plant traded growth for survival by redirecting its carbohydrate and amino acid supplies (Toscano et al., 2019). This poses a central dilemma in plant physiological regulation: optimisation of yield for the production of secondary metabolites may result in a decrease in overall yield and biomass. This effect is referred to as the yield-quality paradox. One of the essential goals of researchers is to overcome this fundamental trade-off, and it is a key aim in designing commercially viable bioactivity enhancement strategies.

3 Environmental Stress as a Natural Elicitor of Bioactive Compounds

Water-Deficit Stress: The Paradox of Drought and Enhanced Quality

Drought stress is generally considered to be a negative occurrence in agriculture and it can cause large losses in yield. But, in the case of medicinal and spice plants, it may increase the content of active substance (Salachna et al., 2024). This is an extraordinary instance of biochemical manipulation. Plants under water stress will close their stomata to retain water in the plant, which will also decrease carbon dioxide (CO_2) uptake, and fixation in the plant through the Calvin cycle, (Saini et al., 2025). This decreases the amount of reduction equivalents (mainly NADPH+H+) that are consumed, which causes a tremendous surplus of reduction equivalents (NADPH+H+) produced during the light-dependent reactions of photosynthesis. The excess energy can drive the metabolism of the plant into the synthesis of highly reduced products (phenols, alkaloids, or isoprenoids) that are frequently the desired secondary metabolites (Kleinwächter & Selmar, 2015).

In the case of Cannabis sativa L., there is a good documented example that plants produce more protective compounds under moderate water-deficit stress conditions, including volatile terpenes and certain secondary metabolites, which will increase the resistance to stress (Sharma et al., 2025). This metabolic shift is associated with the rise of specific cannabinoids, which highlights the ability to influence the quality of the plant with strategic stress during cultivation (Sharma et al., 2025).

The possibilities of this are further enhanced by the consideration of "drought memory. Previous drought exposure has been seen to increase resistance to the next, more severe, drought event (Ali et al., 2025). This implies a highly evolved adaptive process in which the plants biochemically change their processes in response to stress. This means that strategically applying stress (drought priming) in the short term may be sustainable to increase bioactivity (Toscano et al., 2019). The approach would trigger the plant's defense responses and the desired metabolic redirection, but would be halted before biomass is significantly reduced, effectively using the plant's innate memory response to reduce the yield-quality trade-off.

Light and Photoperiod Regulation

Light is a primary environmental factor that profoundly regulates the synthesis and accumulation of plant secondary metabolites (Wu et al., 2025). This regulation is multidimensional, involving light quality,

intensity, and photoperiod. Specific wavelengths of light are recognized by specialized photoreceptors, activating signal transduction networks that either suppress or activate metabolic pathways (Wu et al., 2025). For example, UV light activates the UVR8 photoreceptor, which triggers a signaling pathway involving the HY5 transcription factor, thereby enhancing the biosynthesis of phenolics, flavonoids, and anthocyanins (Jiang et al., 2025; Wu et al., 2025).

Light intensity can dynamically alter the accumulation of secondary metabolites through photosynthetic efficiency, energy allocation and stress responses (Wimalasekera 2019). Although light is required, it will cause photoinhibition and oxidative stress if it is too high, leading to trigger of defense responses and secondary metabolite production (Zhang et al., 2024). This connection between light and oxidative stress is associated with many other environmental stress responses such as drought and temperature extremes. The circadian rhythm system, which is controlled by photoperiod, regulates secondary metabolite biosynthesis, allowing plants to adjust their chemical defenses to daily and seasonal cycles in order to cope with the changes in the environment (Pérez-Llorca & Müller, 2024).

Temperature Extremes: Cold and Heat-Induced Metabolic Shifts

Bioactivity may also be physiologically regulated by temperature stress, either cold or hot. Increased temperatures can cause an increase in reactive oxygen species (ROS) and oxidative stress (Soengas et al., 2018) above a plant's optimal physiological range. In response to this, plants trigger a powerful antioxidant defence system consisting of both enzymatic and non-enzymatic components. Among the enzymatic antioxidants, there are superoxide dismutase (SOD), catalase (CAT), and glutathione reductase (GR) (Zhanassova et al., 2021).

This defense mechanism is one of the key factors behind the increased bioactivity. For example, hot water treatment of broccoli was found to increase the vitamin C and other interesting compounds levels for human health, while the cold water stress increased the inhibitory activity on α-amylase (Šola et al., 2023). In the same way, antioxidant enzymes such as CAT and SOD activities also increase considerably when exposed to cold temperatures (Guo et al., 2022). This process is consistent with a general rule: an array of external stresses, ranging from drought to light to temperature stress, lead to a similar internal response, of oxidative stress, followed by an increase in the very anti-oxidants that have been touted as having pharmacological and nutraceutical properties.

4 Targeted Elicitation Strategies for Controlled Enhancement

The Elicitation Paradigm: From Natural Defense to Industrial Production

A biotechnological approach that can be used to generate secondary metabolites in a controlled environment, such as in vitro cell suspension and hairy root cultures, is the elicitation technique, which involves the use of specific stimuli to accelerate the process of biosynthesis (Trono, 2025).

This paradigm is a departure from using the "untargeted" and possibly harmful impacts of environmental stress applied to the entire environment to a "surgical" approach that targets specific impacts in specific areas. Elicitors are molecules or physical stimuli that activate defense mechanism of the plant and induce metabolic reprogramming and increased synthesis of secondary metabolites (Jain et al., 2024).

Abiotic and Biotic Elicitors

Elicitors can be split into two categories – abiotic, and biotic. Chemical and physical stimuli (abiotic elicitors) are among these external stimuli and some of the well-studied are hormonal compounds that mimic endogenous "alarm" hormones (Jain et al., 2024). Jasmonates (specifically methyl jasmonate, MeJA) and

salicylic acid (SA) play a key role in this approach (Ben et al., 2022). For instance, MeJA triggers the formation of ROS, activates defense-related genes, and triggers hyper-accumulation of secondary metabolites (Ben et al., 2022). Examples of specific increases are a 4.2-fold greater content of phenolics and antioxidant activity in hairy root cultures of Chinese chives (Wang et al., 2022) and a dramatic increase of 6.5-fold in the content of solasodine in hairy root cultures of *Solanum trilobatum* (Shilpha et al., 2015).

Biotic elicitors are of biogenic origin including fungal/bacterial cell wall fragments such as chitosan (Bhaskar et al., 2022). These compounds trigger the plant's immune system, causing induced systemic resistance (ISR), which in results, boosts the production of secondary metabolites (Orozco-Mosqueda et al., 2023). Any elicitor strategy is dependent on a careful optimization of the parameters of the elicitor type, its concentration, the duration of the exposure, and the specific plant culture (Petrova et al., 2024). These parameters can be controlled and elicit is a better approach than broad environmental stress for use in an industrial setting.

Table 1: Overview of elicitors, mechanism of action, and enhanced secondary metabolites

Elicitor Type	Mechanism of Action	Enhanced Compound(s)	Key Source(s)
Methyl Jasmonate	Induces ROS, upregulates defense genes, signals metabolic shift	Phenolics, Antioxidants, Ginsenosides, Lycopene, Solasodine	(Ben et al., 2022).
Salicylic acid	Inhibits α-amylase and α-glucosidase	Hydroxycinnamic acids, flavonoids, Antioxidants, Phenolics	Skrypnik et al., 2022
Chitosan	Mimics pathogen cell wall, activates defense responses	Secondary Metabolites (General)	Strzemski et al., 2025
UV Light	Activates UVR8 receptor, triggers HY5 transcription factor signaling	Phenolics, Flavonoids, Anthocyanins	Morales et al., 2025
Drought	Reduces CO2 uptake, oversupplies NADPH+H+, shifts metabolism	Terpenoids, Cannabinoids	Sharma et al., 2025)

5 Nutritional Modulation of Secondary Metabolism

Nutrient Deficiency as a Metabolic Signal

Nutrient availability is a potent signal that regulates plant metabolism, and under sub-optimal nutrient availability, biosynthesis of secondary metabolites can be induced (Venkatasai et al., 2025). However, in soilless cultivation systems, an improper nutrient solution management can lead to a stress condition, which results in bioactive compounds accumulation (Venkatasai et al., 2025).

But the reaction of a plant to nutrient stressing is not always a rise in the compound of interest. Sulfur deficiency in the model plant Arabidopsis thaliana shows a more complex and subtle regulatory network. Glucosinolates are sulfur rich secondary metabolites, which are synthesized with the help of sulfur (Aarabi et al., 2016). In the absence of sulfur, plants induce a repressor protein (SDI1) which blocks the transcription of the genes involved in glucosinolate biosynthesis (Aarabi et al., 2016). This metabolic arrest allows the small amount of available sulfur to be used for the fundamental metabolism. Two β-glucosidases (BGLU28 and BGLU30) also are activated in parallel to recycle sulfur from the existing glucosinolates, thereby contributing to plant growth (Zhang et al., 2020). The complex repression and catabolism shows that the plant reaction to the nutrient stress is a multi-layered survival strategy, and production of secondary metabolites is a resource-consuming process that can be stimulated or

inhibited by the plant's general metabolic priorities.

Macronutrients (N, P) and their Synergistic Effects

The role of macronutrients such as nitrogen (N) and phosphorus (P) in the modulation of secondary metabolism is complicated and is highly dependent on the situation. The study deals with the ups and downs of *Rubia tinctorum* L. However, (madder) revealed that the application of phosphorous fertilizer, especially in combination with nitrogen fertilizer, and also saline conditions lead to an increase in the amount of flavonoids (Zamani et al., 2014). The study indicates a positive synergistic effect between both nutrients which enable plants to withstand external stress.

Other studies, however, have suggested that raising N fertilizer could result in a decrease in phenolics (Qadir et al., 2017). The seemingly paradoxical results highlight an important principle: the impact of one nutrient does not occur in isolation, but is related to the relative concentration of other nutrients and the presence of other environmental factors. A systems-level approach is thus needed to grasp the effect of nutrient modulation on metabolic flux and secondary metabolite production. Whether and how a nutritional intervention will be successful depends on the overall health of a plant and the type of stress it is experiencing.

6 Cutting-Edge Biotechnological Approaches for Precision Regulation

Genetic Engineering and Genome Editing: The CRISPR/Cas9 Revolution

Besides physiological induction (which is indirect and sometimes unpredictable), genetic modification is a direct and precise approach to improving production of secondary metabolites (Singh 2023). Clustered regularly interspaced short palindromic repeats (CRISPR)/Cas9 system is a revolutionary genome editing technique that enables precise and accurate modification of genetic sequences (Guo et al. 2023). This technology will allow researchers to take a proactive approach to designing and engineering a plant's metabolic blueprint instead of inducing a stress response reactively.

Table 2: Application of CRISPR/Cas9 to manipulate metabolic pathways

Plant Species	Gene Targeted	Modification Strategy	Resulting Bioactivity Change	Key Source(s)
Papaver somniferum	*4'OMT*, *4'OMT2*	Gene knockout	Drastic reduction of benzyl isoquinoline alkaloids (BIAs) like morphine and thebaine.	Aghaali & Naghavi, 2024
N. tabacum	*CsHB1*	Targeted mutation	97.5% decrease in caffeine accumulation in callus.	Ma et al., 2021
Soybean	*GmF3H1*, *GmF3H2*, *GmFNS-1*	Multiplex targeting	Increased isoflavone content in seeds.	Zhang et al., 2020
V. vinifera	VvbZIP36	Targeted mutagenesis	Increased accumulation of anthocyanin.	Tu et al., 2022

The use of this technology is a paradigm shift from a "reactive" to a "proactive" management approach. The researchers are no longer constrained to switching on existing pathways but can engineer the plant's genetic makeup to optimise the yield and efficiency of secondary metabolite production (Al Aboud 2024).

The Multi-Omics Approach: Unraveling Complex Regulatory Networks

Understanding the intricate regulatory networks in the plant is the key to unleashing the full potential of genetic engineering. Thanks to the

multi-omics approach, which combines the analysis of the entire genome, transcriptome, proteome, and metabolome in a high-throughput manner, this has been revolutionized (Satrio et al., 2024). The integration of this information will help to unravel the complex signaling networks and reveal important regulatory nodes that control secondary metabolism. This comprehensive perspective offers a more comprehensive depiction of plant stress perception and response to stress or other elicitors to provide a more effective and targeted means of intervention.

Plant Tissue and Organ Culture

Besides genetic techniques, plant tissue and organ culture systems (including cell suspension culture and hairy root culture) offer a controlled environment for the cultivation of secondary metabolites, circumventing the difficulties associated with field cultivation, such as low yields and seasonal variability (Khalafalla 2025). This platform is often used in conjunction with elicitation strategies that lead to hyper-accumulation of desired compounds in a sterile and consistent environment (Adil et al., 2025).

7 From Lab to Market: Challenges and Socioeconomic Implications

Economic Feasibility and Scalability Hurdles

All the scientific advances still have some way to go before they are ready for commercial production on the industrial level. Expensive and hard-to-scale equipment is needed for technologies that develop advanced formulations, including nanopesticides. Similarly, the implementation of state-of-the-art technologies, such as CRISPR, multi-omics approaches, are also very costly, and this is a problem for their large-scale use (Borah et al., 2024). The combination of scientific potential and economic viability is critical. These technologies will need more research to create economically viable bioproduction systems, and to optimize the entire production chain from raw material to the finished product.

Ethical and Regulatory Considerations

Complex ethical and regulatory issues also emerge because of the use of advanced genetic technologies. However, the public's perception of GMO and the absence of a global regulatory framework pose great challenges in mass adoption of GECs (Daye et al., 2023). Biopiracy (uncontrolled access of TKs without adequate compensation) and the use of unclassified phyto-compounds without adequate dosage standardization are among others ethical issues (Hirakani et al., 2022). These challenges can only be overcome by transparent research, public engagement and the creation of clear, globally harmonized regulatory guidance and standards to protect the safety and efficacy of these products.

Commercial Applications and Market Landscape

The Market for plant-based bioactive compounds is a high-impact, multi-billion dollar industry with close to fast expectations of growth (Palthur et al., 2010). This growth is due to the rising demand of consumers for natural and functional foods, dietary supplements, and therapeutic products with proven health benefits (Suleria et al., 2019).

A new interdependency between traditional agriculture, novel biotechnology, and computational science is apparent in the commercial world. The biostimulants such as Ascend PGRs (Plant Growth Regulators) are commercially available and contain optimized ratios of plant growth hormones (auxin, gibberellic acid and cytokinin) that boost crop growth and stress tolerance (Sible 2019). Also, nutraceutical companies such as ChromaDex and Nuritas are at the forefront of this industry. ChromaDex utilizes patented ingredients like Niagen and Immulina (Craighead et al., 2025). The AI and genomics platform used at Nuritas for discovery of new peptides, highlights the direct application of the technologies covered in the present review to speed up the process of new product development. The use of AI and

genomics to discover new peptides at Nuritas is a direct application of the technologies covered in the present review to speed up the process of new product development. The discovery of these companies confirms that the state of the art technologies to improve bioactivity of plants are not only theoretical but are being commercialized and are starting to change the market.

Conclusion

The science of plant physiological regulation for improved bioactivity has clearly moved on from observation to predictive precision-based engineering. A basic knowledge of the intrinsic stress response of plants, in which environmental stress (such as drought and light) triggers plant defense mechanisms that involve oxidative stress has led to a variety of sophisticated tools. From targeted abiotic and biotic elicitation in controlled bioproduction systems to cutting-edge genome editing and AI-driven discovery, these technologies provide unprecedented levels of control—controlling plant systems to create novel compounds. These range from targeted abiotic and biotic elicitation in controlled bioproduction systems to sophisticated genome editing and AI-driven discovery technologies, providing unprecedented levels of control—manipulated plant systems to produce novel compounds.

The strategic, knowledge-based approach to reducing the impact on biomass and boosting yields of desired compounds is now the central challenge of the yield-quality trade-off. But the next big step will be the gap between scientific innovation and commercialization. This includes ongoing research on improved cost-effective and scalable bioproduction systems and on the creation of clear and harmonized regulatory rules on international level to control the ethical challenges of gene edited crops.

Predictive modeling under the umbrella of seamless integration of multi-omics data, computational biology, and metabolic engineering is the future of this field. The potential for biofortified crops to provide greater therapeutic value can help address urgent challenges in the world such as food security and malnutrition, while simultaneously enabling us to meet the rapidly increasing global demand for high value pharmaceuticals and nutraceuticals by fully exploiting the potential of physiological regulation. The transformative potential is an exciting new prospect for the future of plant science and human health.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: **study design:** Idris, A; **data collection:** Idris, A, Mohammad. M; **analysis and interpretation of results:** Mohammad. M; **draft manuscript preparation:** Idris A. All authors reviewed the results and approved the final version of the manuscript.

References

Aarabi, F., Kusajima, M., Tohge, T., Konishi, T., Gigolashvili, T., Takamune, M., & Maruyama-Nakashita, A. (2016). Sulfur deficiency–induced repressor proteins optimize glucosinolate biosynthesis in plants. Science Advances, 2(10), e1601087.

Adil, M., Younas, Z., Ahmad, I., Al Rohily, K. M., & Mashwani, Z. U. R. (2025). Elicitation of *Withania somnifera* adventitious roots: in-vitro cultures for enhanced secondary metabolites synthesis. Horticulture, Environment, and Biotechnology, 1-11.

Aghaali, Z., & Naghavi, M. R. (2024). Developing benzylisoquinoline alkaloid-enriched

opium poppy via CRISPR-directed genome editing: A review. BMC Plant Biology, 24(1), 700.

Ahlawat, Y. K., Singh, M., Manorama, K., Lakra, N., Zaid, A., & Zulfiqar, F. (2024). Plant phenolics: neglected secondary metabolites in plant stress tolerance. Brazilian Journal of Botany, 47(3), 703-721.

Al Aboud, N. M. (2024). Unlocking the genetic potential: Strategies for enhancing secondary metabolite biosynthesis in plants. Journal of the Saudi Society of Agricultural Sciences, 23(8), 542-554.

Ali, S., Mir, R. A., Haque, M. A., Danishuddin, Almalki, M. A., Alfredan, M., & Mir, Z. A. (2025). Exploring physiological and molecular dynamics of drought stress responses in plants: challenges and future directions. Frontiers in Plant Science, 16, 1565635.

Ben Romdhane, A., Chtourou, Y., Sebii, H., Baklouti, E., Nasri, A., Drira, R., & Fki, L. (2022). Methyl jasmonate induces oxidative/nitrosative stress and the accumulation of antioxidant metabolites in Phoenix dactylifera L. Biotechnology Letters, 44(11), 1323-1336.

Bhaskar, R., Xavier, L. S. E., Udayakumaran, G., Kumar, D. S., Venkatesh, R., & Nagella, P. (2022). Biotic elicitors: a boon for the in-vitro production of plant secondary metabolites. Plant Cell, Tissue and Organ Culture (PCTOC), 149(1), 7-24.

Bolat, E., Sarıtaş, S., Duman, H., Eker, F., Akdaşçi, E., Karav, S., & Witkowska, A. M. (2024). Polyphenols: secondary metabolites with a biological impression. Nutrients, 16(15), 2550.

Borah, A., Singh, S., Chattopadhyay, R., Kaur, J., & Bari, V. K. (2024). Integration of CRISPR/Cas9 with multi-omics technologies to engineer secondary metabolite productions in medicinal plant: Challenges and Prospects. Functional & Integrative Genomics, 24(6), 207.

Craighead, D., McCarty, N., Freeberg, K., Udovich, C., Hess, M., Facey, M., & Seals, D. (2025). Nicotinamide Riboside Lowers Systolic Blood Pressure and Improves Vascular Endothelial Function in Midlife/Older Adults with Above-Normal Systolic Blood Pressure. Physiology, 40(S1), 1901.

Dayé, C., Spök, A., Allan, A. C., Yamaguchi, T., & Sprink, T. (2023). Social acceptability of cisgenic plants: public perception, consumer preferences, and legal regulation. In Cisgenic crops: Safety, legal and social issues (pp. 43-75). Cham: Springer International Publishing.

Erb, M., & Kliebenstein, D. J. (2020). Plant secondary metabolites as defenses, regulators, and primary metabolites: the blurred functional trichotomy. Plant physiology, 184(1), 39-52.

Fazili, M. A., Bashir, I., Ahmad, M., Yaqoob, U., & Geelani, S. N. (2022). In vitro strategies for the enhancement of secondary metabolite production in plants: a review. Bulletin of the National Research Centre, 46(1), 35.

Guo, Y., Zhao, G., Gao, X., Zhang, L., Zhang, Y., Cai, X., & Guo, X. (2023). CRISPR/Cas9 gene editing technology: a precise and efficient tool for crop quality improvement. Planta, 258(2), 36.

Guo, Z., Cai, L., Liu, C., Chen, Z., Guan, S., Ma, W., & Pan, G. (2022). Low-temperature stress affects reactive oxygen species, osmotic adjustment substances, and antioxidants in rice (*Oryza sativa* L.) at the reproductive stage. Scientific Reports, 12(1), 6224.

Hirakani, Z. M., Ansari, M. F., & Shukla, V. (2022). Current Advancement and Future Challenges for Phytomedicines. ResearchGate Link.

Hossain, M. S., Ye, W., Hossain, M. A., Okuma, E., Uraji, M., Nakamura, Y., & Murata, Y. (2013). Glucosinolate degradation products, isothiocyanates, nitriles, and thiocyanates, induce stomatal closure accompanied by peroxidase-mediated

reactive oxygen species production in Arabidopsis thaliana. Bioscience, biotechnology, and biochemistry, 77(5), 977-983.

Jain, D., Bisht, S., Parvez, A., Singh, K., Bhaskar, P., & Koubouris, G. (2024). Effective biotic elicitors for augmentation of secondary metabolite production in medicinal plants. Agriculture, 14(6), 796.

Jan, R., Asaf, S., Numan, M., Lubna, & Kim, K. M. (2021). Plant secondary metabolite biosynthesis and transcriptional regulation in response to biotic and abiotic stress conditions. Agronomy, 11(5), 968.

Jiang, N., García Navarrete, T., Lee, Y. S., Pawlowski, E. G., Park, S., & Grotewold, E. (2025). Flavonoid pathway intermediates implicate UVR8 in functions beyond canonical UV-B signaling. Nature Communications, 16(1), 7810.

Khalafalla, M. M. (2025). Plant Cell Suspension Culture for Plant Secondary Metabolite Production: Current Status, Constraints, and Future Solutions. Pol. J. Environ. Stud, 1-14.

Kleinwächter, M., & Selmar, D. (2015). New insights explain that drought stress enhances the quality of spice and medicinal plants: potential applications. Agronomy for sustainable development, 35(1), 121-131.

Kumar, A., & Kumar, S. (Eds.). (2024). Secondary metabolites and biotherapeutics. Elsevier.

Ma, W., Kang, X., Liu, P., Zhang, Y., Lin, X., Li, B., & Chen, Z. (2021). The analysis of transcription factor CsHB1 effects on caffeine accumulation in tea callus through CRISPR/Cas9 mediated gene editing. Process Biochemistry, 101, 304-311.

Morales, L. O., Shapiguzov, A., Rai, N., Aphalo, P. J., & Brosché, M. (2025). Protection of photosynthesis by UVR8 and cryptochromes in Arabidopsis under blue and UV radiation. Plant, Cell & Environment.

Orozco-Mosqueda, C. (2023). Unraveling efficient strategies for inducing systemic resistance in crops for managing biotic stress. Plant Stress, 8, 100156.

Palthur, M. P., Palthur, S. S., & Chitta, S. K. (2010). Nutraceuticals: Concept and regulatory scenario. Int. J. Pharm. Pharm. Sci, 2(2), 14-20.

Pérez-Llorca, M., & Müller, M. (2024). Unlocking nature's rhythms: insights into secondary metabolite modulation by the circadian clock. International Journal of Molecular Sciences, 25(13), 7308.

Petrova, M., Miladinova-Georgieva, K., & Geneva, M. (2024). Influence of abiotic and biotic elicitors on organogenesis, biomass accumulation, and production of key secondary metabolites in Asteraceae plants. International Journal of Molecular Sciences, 25(8), 4197.

Qadir, O., Siervo, M., Seal, C. J., & Brandt, K. (2017). Manipulation of contents of nitrate, phenolic acids, chlorophylls, and carotenoids in lettuce (*Lactuca sativa* L.) via contrasting responses to nitrogen fertilizer when grown in a controlled environment. Journal of Agricultural and Food Chemistry, 65(46), 10003-10010.

Saini, N., Vijayvergia, R., & Kumar, A. (2025). Responses of Medicinal Plants to Drought: Implications for Secondary Metabolite Production. Journal of Stress Physiology & Biochemistry, 21(2), 167-186.

Salachna, P., Wesołowska, A., Zawadzińska, A., Kańczurzewska, M., Sawikowska, A., Darras, A., & Piechocki, R. (2024). Flaxseed oil cake improves basil (*Ocimum basilicum* L.) yield under drought stress by increasing herb biomass and quality of essential oil. Industrial Crops and Products, 220, 119295.

Satrio, R. D., Fendiyanto, M. H., & Miftahudin, M. (2024). Tools and techniques used at

global scale through genomics, transcriptomics, proteomics, and metabolomics to investigate plant stress responses at the molecular level. In Molecular dynamics of plant stress and its management (pp. 555-607). Singapore: Springer Nature Singapore.

Sharma, S., Alberti, T., De Sarandy Raposo, R., Anterola, A. M., Weber, J., Diatta, A. A., & Da Cunha Leme Filho, J. F. (2025). The effects of water-deficit stress on *Cannabis sativa* L. development and production of secondary metabolites: A review. Horticulturae, 11(6), 646.

Shende, V. V., Bauman, K. D., & Moore, B. S. (2024). The shikimate pathway: gateway to metabolic diversity. Natural product reports, 41(4), 604-648.

Shilpha, J., Satish, L., Kavikkuil, M., Largia, M. J. V., & Ramesh, M. (2015). Methyl jasmonate elicits the solasodine production and anti-oxidant activity in hairy root cultures of *Solanum trilobatum* L. Industrial Crops and Products, 71, 54-64.

Sible, C. N. (2019). Plant growth regulators and biostimulants for use in varying management systems to improve corn grain yield (Doctoral dissertation, University of Illinois at Urbana-Champaign).

Singh, H. (2023). Enhancement of plant secondary metabolites by genetic manipulation. In Genetic manipulation of secondary metabolites in medicinal plant (pp. 59-90). Singapore: Springer Nature Singapore.

Singh, V. (2025). Nutraceutical Companies and Startups Revolutionizing Food Tech - GreyB, accessed September 1, 2025, https://www.greyb.com/blog/nutraceutical-companies-and-startups/

Skrypnik, L., Golovin, A., & Savina, T. (2022). Effect of salicylic acid on phenolic compounds, antioxidant and antihyperglycemic activity of Lamiaceae plants grown in a temperate climate. Frontiers in Bioscience-Elite, 14(1), 3.

Soengas, P., Rodríguez, V. M., Velasco, P., & Cartea, M. E. (2018). Effect of temperature stress on antioxidant defenses in Brassica oleracea. ACS omega, 3(5), 5237-5243.

Šola, I., Davosir, D., Kokić, E., & Zekirovski, J. (2023). Effect of hot-and cold-water treatment on broccoli bioactive compounds, oxidative stress parameters and biological effects of their extracts. Plants, 12(5), 1135.

Sreenivasulu, N., & Fernie, A. R. (2022). Diversity: current and prospective secondary metabolites for nutrition and medicine. Current opinion in Biotechnology, 74, 164-170.

Stephane, F. F. Y. (2020). Terpenoids as Important Bioactive. Essential oils: bioactive compounds, new perspectives and applications, 75.

Strzemski, M., Dresler, S., Hawrylak-Nowak, B., Tkaczyk, P., Kulinowska, M., Feldo, M., & Hanaka, A. (2025). Chitosan elicitation enhances biomass and secondary metabolite production in *Carlina acaulis* L. Scientific Reports, 15(1), 23411.

Suleria, H. A. R., & Barrow, C. (Eds.). (2019). Bioactive compounds from plant origin: extraction, applications, and potential health benefits. CRC Press.

Toscano, S., Trivellini, A., Cocetta, G., Bulgari, R., Francini, A., Romano, D., & Ferrante, A. (2019). Effect of preharvest abiotic stresses on the accumulation of bioactive compounds in horticultural produce. Frontiers in plant science, 10, 1212.

Toscano, S., Trivellini, A., Cocetta, G., Bulgari, R., Francini, A., Romano, D., & Ferrante, A. (2019). Effect of preharvest abiotic stresses on the accumulation of bioactive compounds in horticultural produce. Frontiers in plant science, 10, 1212.

Trono, D. (2025). Elicitation as a tool to improve the accumulation of secondary metabolites in *Cannabis sativa.* Phytochemistry Reviews, 24(4), 3119-3155.

Tu, M., Fang, J., Zhao, R., Liu, X., Yin, W., Wang, Y., & Fang, Y. (2022). CRISPR/Cas9-mediated mutagenesis of VvbZIP36 promotes anthocyanin accumulation in grapevine (*Vitis vinifera*). Horticulture research, 9, uhac022.

Upadhyay, R., Saini, R., Shukla, P. K., & Tiwari, K. N. (2025). Role of secondary metabolites in plant defense mechanisms: A molecular and biotechnological insights. Phytochemistry Reviews, 24(1), 953-983.

Urbancsok, J., Bones, A. M., & Kissen, R. (2017). Glucosinolate-derived isothiocyanates inhibit Arabidopsis growth and the potency depends on their side chain structure. International Journal of Molecular Sciences, 18(11), 2372

Venkatasai, N. N., Shetty, D. N., Vinay, C. M., Sekar, M., Muthusamy, A., & Rai, P. S. (2025). A comprehensive review of factors affecting growth and secondary metabolites in hydroponically grown medicinal plants. Planta, 261(3), 48.

Wang, C., Zhang, J., Xie, J., Yu, J., Li, J., Lv, J., & Patience, B. E. (2022). Effects of preharvest methyl jasmonate and salicylic acid treatments on growth, quality, volatile components, and antioxidant systems of Chinese chives. Frontiers in Plant Science, 12, 767335.

Wimalasekera, R. (2019). Effect of light intensity on photosynthesis. Photosynthesis, productivity and environmental stress, 65-73.

Wu, S., Chen, W., Lu, S., Zhang, H., & Yin, L. (2022). Metabolic engineering of shikimic acid biosynthesis pathway for the production of shikimic acid and its branched products in microorganisms: advances and prospects. Molecules, 27(15), 4779.

Wu, W., Wu, H., Liang, R., Huang, S., Meng, L., Zhang, M., & Zhu, H. (2025). Light regulates the synthesis and accumulation of plant secondary metabolites. Frontiers in Plant Science, 16, 1644472.

Zamani, Z., Zeinali, H., MASOOD, S. J., & Madani, H. (2014). Effect of nitrogen and phosphorous fertilizers on the yield and secondary metabolites of medicinal plant *Rubia tinctorum* L. under salinity conditions.

Zhanassova, K., Kurmanbayeva, A., Gadilgereyeva, B., Yermukhambetova, R., Iksat, N., Amanbayeva, U., & Masalimov, Z. (2021). ROS status and antioxidant enzyme activities in response to combined temperature and drought stresses in barley. Acta Physiologiae Plantarum, 43(8), 114.

Zhang, L., Kawaguchi, R., Morikawa-Ichinose, T., Allahham, A., Kim, S. J., & Maruyama-Nakashita, A. (2020). Sulfur deficiency-induced glucosinolate catabolism attributed to two β-glucosidases, BGLU28 and BGLU30, is required for plant growth maintenance under sulfur deficiency. Plant and Cell Physiology, 61(4), 803-813.

Zhang, M., Ming, Y., Wang, H. B., & Jin, H. L. (2024). Strategies for adaptation to high light in plants. Abiotech, 5(3), 381-393.

Zhang, P., Du, H., Wang, J., Pu, Y., Yang, C., Yan, R., & Yu, D. (2020). Multiplex CRISPR/Cas9-mediated metabolic engineering increases soya bean isoflavone content and resistance to soya bean mosaic virus. Plant biotechnology journal, 18(6), 1384-1395.