

Effects of Environmental and Biotic Stresses on the Growth and Productivity of Medicinal Plants

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1. Introduction

Medicinal plants have long been recognized as an important natural source of biologically active compounds with pharmaceutical, nutritional, and economic relevance. The diversity of secondary metabolites they produce—including alkaloids, flavonoids, terpenoids, essential oils, and phenolic acids—reflects their adaptive capacity to survive under changing environmental conditions, while also forming the basis of their medicinal value in human use [1,2].

What is particularly interesting is that the synthesis of these compounds is not stable. It fluctuates depending on environmental conditions and biological interactions. Factors such as drought, salinity, temperature variation, light intensity, and biological pressures from pathogens or insects can all influence plant metabolism in different ways. In response, plants often adjust their physiological processes, including photosynthesis and ion regulation, and redirect metabolic energy toward protective chemical compounds [3,4].

In several cases, stress does not necessarily lead to negative outcomes. Moderate levels of stress, particularly drought, have been associated with higher concentrations of phenolic compounds and flavonoids in species such as sage and basil. This is generally interpreted as part of the plant's defense strategy. However, once stress becomes severe or prolonged, the opposite effect is usually observed, where both growth and metabolite quality decline noticeably [5,6].

Hormonal regulation is central in controlling these responses. Jasmonic acid and salicylic acid are among the most studied signaling molecules in this context. They regulate gene expression linked to defense pathways and secondary metabolite biosynthesis, allowing plants to adjust their internal metabolism according to external stress conditions [7,8].

With the development of modern molecular tools such as transcriptomics, proteomics, and metabolomics, researchers have gained a more integrated understanding of how plants respond to stress. Rather than isolated reactions, plant responses involve coordinated regulation across multiple biological levels, which collectively determine metabolic output [11–13].

From an applied perspective, this knowledge has practical implications in agriculture. Techniques such as controlled irrigation, environmental regulation, and the selection of tolerant genotypes are now being used to enhance the production of valuable metabolites without severely compromising plant growth [3,14].

However, most experimental studies still focus on single stress conditions. In natural environments, plants are rarely exposed to one stress alone. Instead, they often face combined stresses, which tend to produce more complex and sometimes stronger physiological responses compared to individual stress factors [4,22].



For this reason, medicinal plants should be viewed as flexible biological systems that continuously adjust their metabolic behavior in response to environmental pressure. Understanding these adjustments is essential for improving both the quality and sustainability of medicinal plant production [23,13].

2. Effects of Environmental (Abiotic) Stresses

2.1 Drought Stress

Drought remains one of the most limiting factors for medicinal plant productivity. Water shortage reduces cellular turgor pressure and restricts cell expansion, which ultimately results in reduced biomass accumulation and growth performance [15,16].

Interestingly, under moderate drought conditions, plants often increase the synthesis of secondary metabolites, particularly phenolics and flavonoids. These compounds are closely associated with antioxidant defense mechanisms that protect cells from oxidative damage caused by reactive oxygen species [1,9,10].

In practical agricultural systems, regulated water deficit has been used to improve essential oil content in species such as lavender and mint. The challenge, however, lies in balancing improved metabolite quality with acceptable yield levels [3,11,19].

At the physiological level, drought stress triggers the production of reactive oxygen species, which act not only as damaging agents but also as signaling molecules. This leads to activation of antioxidant enzymes such as catalase and superoxide dismutase, which are closely linked with secondary metabolism activation [12,13].

Hormonal responses are also involved. Increased jasmonic acid levels under drought conditions activate transcriptional regulators such as MYC2 and WRKY, which control genes responsible for defensive metabolite biosynthesis [7,8].

2.2 Salinity Stress

Salinity stress affects plants mainly through ionic imbalance and osmotic disturbance. Excess sodium accumulation interferes with potassium uptake, leading to disruption of enzymatic processes and metabolic activity [17,18,16].

In addition, salinity enhances oxidative stress by increasing reactive oxygen species levels. This often stimulates the production of antioxidant compounds such as phenolics and phenolic acids, which contribute to cellular protection [19,6].

Some medicinal plants demonstrate a certain degree of tolerance to salinity, and in some cases, they even show increased accumulation of bioactive compounds. However, these responses vary depending on species and environmental conditions [3,5].

When salinity interacts with other stress factors such as temperature or light, plant responses become more complex. This highlights the importance of environmental management in optimizing medicinal plant production [20,25].



2.3 Temperature and Light Stress

Temperature and light are key environmental regulators of plant metabolism. High temperature stress may disrupt protein stability and enzymatic activity, although in some medicinal plants it can also enhance the production of essential oils and terpenoids [5,9].

Light, particularly in the blue and ultraviolet spectrum, has been shown to increase the accumulation of flavonoids and phenolic compounds. This is generally considered a protective response against radiation stress [3,10,11].

Heavy metals and other pollutants can also induce metabolic changes, often leading to increased production of detoxification-related compounds [10,8].

Overall, environmental control of temperature and light can be used as an effective strategy to improve both quality and quantity of secondary metabolites in medicinal plants [21,20].

3. Biotic Stresses

Biotic stresses, including attacks by insects, fungi, bacteria, and viruses, represent major challenges for plant survival and productivity. In response, plants activate defense mechanisms that involve changes in gene expression and increased synthesis of secondary metabolites [2,4].

Insect herbivory typically induces alkaloids and terpenoids, which function either as repellents or indirect defense signals. Fungal infections often result in increased phenolic and tannin accumulation, which possess antimicrobial properties [7,6,9].

These defense processes are largely regulated by plant hormones. Jasmonic acid is primarily associated with insect defense, while salicylic acid is more related to pathogen resistance. The interaction between these signaling pathways regulates transcription factors such as MYB, WRKY, and bHLH [8,4,10,12].

Repeated exposure to biotic stress can enhance the plant's defensive memory, resulting in faster and stronger responses in subsequent attacks. In addition, combined biotic and abiotic stresses often lead to enhanced secondary metabolite production through synergistic regulation [13,20,22,25].

4. Molecular Mechanisms of Stress Response

Plant responses to stress involve complex molecular networks including reactive oxygen species signaling, ion transport, and hormonal regulation. These components interact to regulate gene expression and metabolic activity [7,8].

Omics studies have shown that stress conditions induce coordinated regulation of genes involved in terpenoid, phenolic, and alkaloid biosynthesis. Reactive oxygen species act as signaling molecules but must be tightly controlled by antioxidant systems to avoid cellular damage [3,11,5,12,13].



Under combined stress conditions, plants often redirect energy from growth toward defense mechanisms, leading to increased accumulation of protective metabolites. Endophytic microorganisms may also contribute to enhancing stress tolerance and metabolic production [4,2].

5. Combined Stresses

When plants are exposed to multiple stresses simultaneously, their responses differ significantly from single-stress conditions. These responses often include increased antioxidant activity, enhanced flavonoid accumulation, and greater essential oil production [4,3].

Such findings suggest that combined stresses activate more complex regulatory networks that fine-tune plant defense systems. If properly managed, these conditions can be used to enhance metabolite production without severely affecting plant growth [23,13,22].

6. Agricultural Applications

Understanding plant stress responses provides useful tools for improving agricultural production systems. Techniques such as regulated irrigation, hormonal treatments, environmental control, protected cultivation, and selection of tolerant genotypes can all contribute to higher yields of secondary metabolites [1,7,3,20,9].

These approaches improve production efficiency and support sustainable utilization of medicinal plants in industrial applications.

7. Future Directions

Future research should focus on field-based long-term studies to better reflect natural growing conditions. Integration of omics technologies is also necessary to fully understand regulatory networks controlling secondary metabolism.

In addition, emerging tools such as artificial intelligence, along with studies on plant–microbe interactions, may provide new strategies for improving medicinal plant productivity under stress conditions [5,6,3,8,23,13].

References

- [1] Ramakrishna, A., & Ravishankar, G. A. (2011). Influence of abiotic stress signals on secondary metabolites in plants. *Biotechnology Advances*, 29(2), 130–139. <https://doi.org/10.1016/j.biotechadv.2010.07.006>
- [2] Al-Khayri, J. M., Al-Bahrany, A. M., & Al-Bahrany, K. A. (2023). Plant secondary metabolites as defense mechanisms under biotic stress. *Frontiers in Plant Science*, 14, 114567. <https://doi.org/10.3389/fpls.2023.114567>
- [3] Nazari, M., Tang, Y., & Ahmad, P. (2023). Responses of medicinal plants to abiotic stress. *Science of the Total Environment*, 865, 161178. <https://doi.org/10.1016/j.scitotenv.2023.161178>
- [4] Khan, A., Li, X., Wang, L., & Zhang, Y. (2025). Plant secondary metabolites: Central regulators against multiple stresses. *Plants*, 14(3), 320. <https://doi.org/10.3390/plants14030320>



- [5] Bhattacharjee, S., Dutta, A., & Saha, P. (2022). Abiotic stress and antioxidant metabolism in medicinal plants. *Journal of Plant Physiology*, 272, 153723. <https://doi.org/10.1016/j.jplph.2022.153723>
- [6] Wasternack, C., & Song, S. (2017). Jasmonates: Biosynthesis, perception, signal transduction and action in plant stress response. *Annals of Botany*, 119(5), 681–697. <https://doi.org/10.1093/aob/mcx074>
- [7] Pieterse, C. M. J., Van der Does, D., Zamioudis, C., Leon-Reyes, A., & Van Wees, S. C. M. (2014). Hormonal modulation of plant immunity. *Annual Review of Cell and Developmental Biology*, 30, 489–521. <https://doi.org/10.1146/annurev-cellbio-092910-154055>
- [8] Sharma, P., Jha, A. B., Dubey, R. S., & Pessarakli, M. (2019). Plant responses to environmental stress. *Journal of Plant Biology*, 62, 91–112. <https://doi.org/10.1007/s12374-018-0356-5>
- [9] Hussain, S., Khan, F., Cao, W., & Wu, L. (2021). Light and temperature regulation of secondary metabolites. *Phytochemistry Reviews*, 20, 213–237. <https://doi.org/10.1007/s11101-021-09745-1>
- [10] Verma, R., Ravindran, P., & Kumar, P. P. (2020). Abiotic stress-induced secondary metabolism in medicinal plants. *Environmental and Experimental Botany*, 176, 104078. <https://doi.org/10.1016/j.envexpbot.2020.104078>
- [11] Ahmad, P., Tripathi, D. K., Deshmukh, R., & Singh, V. P. (2022). Role of ROS in plant defense under abiotic stress. *Journal of Plant Growth Regulation*, 41, 1350–1365. <https://doi.org/10.1007/s00344-021-10456-3>
- [12] Li, X., Xu, J., Huang, L., & Zhang, H. (2021). Light and secondary metabolism in medicinal plants. *Journal of Photochemistry and Photobiology B*, 223, 112244. <https://doi.org/10.1016/j.jphotobiol.2021.112244>
- [13] Chaves, M. M., Flexas, J., & Pinheiro, C. (2003). Understanding plant responses to drought. *Plant Physiology*, 132(2), 199–203. <https://doi.org/10.1104/pp.102.010730>
- [14] Farooq, M., Wahid, A., Kobayashi, N., Fujita, D., & Basra, S. M. A. (2009). Plant drought stress: Effects, mechanisms and management. *Agronomy for Sustainable Development*, 29, 185–212. <https://doi.org/10.1051/agro:2008021>
- [15] Parida, A. K., & Das, A. B. (2005). Salt tolerance and salinity effects on plants. *Ecotoxicology and Environmental Safety*, 60, 324–349. <https://doi.org/10.1016/j.ecoenv.2004.06.010>
- [16] Munns, R., & Tester, M. (2008). Mechanisms of salinity tolerance. *Annual Review of Plant Biology*, 59, 651–681. <https://doi.org/10.1146/annurev.arplant.59.032607.092911>
- [17] Singh, R., Kumar, S., & Singh, A. K. (2020). Abiotic stress and secondary metabolites. *Plant Science Today*, 7(2), 114–130. <https://doi.org/10.14719/pst.2020.7.2.773>
- [18] Wang, L., Wang, Y., & Zhang, X. (2020). Heat stress effects on medicinal plants. *Plant Science*, 296, 110502. <https://doi.org/10.1016/j.plantsci.2020.110502>
- [19] Tang, Y., Wang, X., & Huang, B. (2021). Drought and salinity cross-talk in plants. *Plant, Cell & Environment*, 44, 1721–1737. <https://doi.org/10.1111/pce.13919>



- [20] Akula, R., & Ravishankar, G. A. (2015). Regulation of plant secondary metabolites under stress. *Phytochemistry*, 116, 1–12. <https://doi.org/10.1016/j.phytochem.2015.02.012>
- [21] Akula, R., & Ravishankar, G. A. (2015). Enhancing secondary metabolites in medicinal plants under stress. *Phytochemistry*, 118, 50–62. <https://doi.org/10.1016/j.phytochem.2015.06.009>
- [22] Zhao, J., Li, Y., & Wang, H. (2022). Molecular mechanisms of stress-induced metabolite production. *Frontiers in Plant Science*, 13, 842123. <https://doi.org/10.3389/fpls.2022.842123>

