



PLANT CHEMISTRY

Plant Secondary Metabolites in Ecological, Biochemical, and Agricultural Systems

Edited by Azamal Husen



CRC Press
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Plant Secondary Metabolites in Ecological, Biochemical, and Agricultural Systems

Plants survive in complex and competitive environments by producing an extraordinary array of secondary metabolites that protect, signal, and strengthen them under stress. *Plant Secondary Metabolites in Ecological, Biochemical, and Agricultural Systems* offers a comprehensive exploration of these powerful natural compounds and their multifaceted roles in plant defense, ecological interactions, and sustainable crop production. Bringing together cutting-edge scientific insights from plant biochemistry, ecology, and agriculture, this volume examines major classes of secondary metabolites, their biosynthesis, stress responses, ecological roles, and applications in modern farming. With the increasing demand for environmentally safe alternatives to synthetic agrochemicals, this book highlights how natural plant compounds can support pest management, improve crop resilience, enhance soil health, and reduce environmental impact. An essential reference for researchers, advanced students, agricultural professionals, and biotechnologists, this book provides timely knowledge and practical perspectives for developing future sustainable farming strategies grounded in nature's own defense mechanisms.

Salient features:

- Provides an in-depth understanding of how plant secondary metabolites support natural defense, stress tolerance, and ecological interactions.
- Highlights eco-friendly, biologically grounded alternatives to synthetic pesticides, fertilizers, and growth regulators for sustainable agriculture.
- Integrates biochemistry, ecology, molecular biology, and agricultural science to present a holistic perspective on plant defense systems.
- Includes cutting-edge scientific advances in metabolic engineering, genomics, and biotechnology for enhancing crop protection and productivity.
- Serves as a valuable reference for researchers, postgraduate students, biotechnologists, and agricultural professionals working toward sustainable farming solutions.



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Nilofer, Faria Fatima, and Mohammad Israil Ansari*

19.1 INTRODUCTION

Being immobile, plants are continuously subjected to changing environmental conditions and have gradually developed complex biochemical and physiological mechanisms to withstand various biotic and abiotic challenges. Among these adaptive strategies, the synthesis of secondary metabolites (SMs) plays a crucial role in enhancing plant survival, fitness, and ecological interactions. In contrast to primary metabolites, such as carbohydrates, amino acids, nucleotides, and lipids, which are essential for plant growth and development, secondary metabolites do not take part directly in fundamental metabolic activities. Instead, they serve highly specialized functions, contributing to defense mechanisms, reproductive success, and communication with the surrounding environment (Kumar et al. 2020). Secondary metabolites are broadly classified into three major categories based on their biosynthetic origins: alkaloids, phenolics, and terpenoids. Alkaloids, derived mainly from amino acids, are nitrogenous compounds recognized for their potent bioactivity, with well-known examples including morphine, nicotine, and quinine. Phenolic compounds, such as flavonoids, tannins, and lignins, originate from the shikimate and phenylpropanoid pathways and are known for their antioxidant capabilities and roles in UV protection (Roaa 2020). Terpenoids, also known as isoprenoids, represent the largest and most structurally varied group of secondary metabolites. They are produced via the mevalonate and methylerythritol phosphate pathways and encompass important compounds such as gibberellins, carotenoids, and essential oils (Böttger et al. 2018). The ecological functions of secondary metabolites are diverse and frequently stress-specific. These compounds serve as chemical deterrents against herbivores, pathogens, and competing plant species (allelopathy), while also acting as attractants for pollinators and seed dispersers. Moreover, SMs facilitate beneficial plant–microbe interactions, such as symbiosis with nitrogen-fixing bacteria and mycorrhizal fungi, underscoring their multifaceted ecological roles (Khan et al. 2025). Environmental factors are now widely acknowledged as significant regulators of secondary metabolite production. Biotic stresses, such as pathogen

invasion, herbivore feeding, and competition with other species and abiotic challenges such as drought, salinity, extreme temperatures, ultraviolet radiation, and heavy metal contamination, strongly affect the synthesis, profile, and turnover of these compounds. The plant's response to such stresses is mediated by intricate signaling cascades, in which phytohormones, including jasmonic acid (JA), salicylic acid (SA), abscisic acid (ABA), and ethylene, play central roles. These hormones coordinate the regulation of gene expression and enzymatic activity across transcriptional, translational, and post-translational stages (Jan et al. 2021). Such stress-induced metabolic responses reflect a finely tuned reprogramming of cellular metabolism, wherein carbon fluxes are redirected from primary metabolism toward secondary metabolic pathways. For example, during drought stress, plants often enhance the production of phenolic compounds to mitigate oxidative damage caused by reactive oxygen species (ROS). Likewise, UV-B exposure triggers the synthesis of flavonoids and other phenolic derivatives, which function as effective UV screens and strong antioxidants (Meraj et al. 2020). In light of climate change and escalating environmental unpredictability, understanding the molecular and regulatory mechanisms governing stress-responsive secondary metabolite production has garnered significant scientific interest. These insights not only deepen our understanding of plant adaptive physiology but also open avenues for practical applications in agriculture, biotechnology, and medicine. Metabolic engineering of secondary metabolite biosynthetic pathways, for example, holds promise for the development of stress-resilient crop varieties, thereby contributing to sustainable agricultural practices and improved productivity under adverse environmental conditions (Aguirre-Becerra et al. 2020). This chapter explores the intricate relationship between environmental stressors and the production of secondary metabolites in plants, with emphasis on the molecular, biochemical, and ecological aspects of these interactions. Emphasis is placed on elucidating how plants strategically regulate and utilize secondary metabolites to mitigate stress, maintain homeostasis, and thrive in diverse and dynamic ecosystems (Ashraf et al. 2018).