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Metabolomic Shifts in Plants Under Dual Attack by Herbivores and Pathogens

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Abstract: -

In the field, crops are often challenged by insects and disease-causing microbes at the same time, and this combined pressure can drastically reduce plant vigor and yield. When such simultaneous attacks occur, plants activate a network of defense responses that are mainly coordinated through the jasmonic acid (JA) and salicylic acid (SA) pathways. Yet, these two signaling routes frequently interfere with one another; strengthening one can weaken the other, leaving plants less capable of managing both stresses efficiently. Metabolomics, an approach that examines broad sets of metabolites, has become essential for uncovering the chemical shifts that occur under dual stress conditions. During combined herbivore and pathogen attack, plants often reorganize their pools of defense-related secondary metabolites, including phenolics, alkaloids, terpenoids, and glucosinolates. Volatile organic compounds are also altered, affecting communication with insects and microbes in the surrounding environment. At the same time, heightened oxidative stress pushes plants to increase antioxidant molecules that help protect cells from damage. Gaining a detailed understanding of these metabolic changes is key to advancing sustainable crop protection. Metabolomic insights can support breeding programs aimed at designing varieties with stronger and more balanced defenses, improve biological control strategies, and refine precision-focused integrated pest and disease management. Ultimately, exploring metabolomic responses to dual attack equips us with the knowledge needed to build more resilient cropping systems as pest and disease pressures intensify under future climate scenarios.

Keywords: - *Metabolomics, Dual-attack, Herbivores, Pathogens, Salicylate, VOCs, IPM*

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1. Introduction:

Plants growing in farms and natural landscapes are constantly exposed to harmful insects and disease-causing microbes. These stress factors often strike at the same time, and when they do, the damage to crops is usually much more severe than when a plant faces only a single threat (Glazebrook, 2005). Insect herbivores feed on leaves, stems, or roots externally or even inside the plant, whereas fungi, bacteria, and viruses invade plant cells and interfere with normal growth and physiology (Stout *et al*., 2006). With climate change expanding pest ranges and altering disease cycles, such combined attacks are becoming increasingly common worldwide.

To survive these challenges, plants produce a vast array of metabolites, some necessary for growth and development, and others specifically involved in defense signaling and protection (Piasecka *et al*., 2015). These defense chemicals are regulated through intricate hormonal pathways. Typically, chewing or sucking insects stimulate jasmonic acid (JA)-mediated defenses that suppress herbivore survival (Howe & Jander, 2008), while biotrophic pathogens trigger salicylic acid (SA) pathways that help limit infection spread (Fu & Dong, 2013). Seasonal variability in herbivore abundance, as documented in tomato agroecosystems (Singh *et al*., 2023), further demonstrates how fluctuating insect pressure can intensify dual-stress metabolomic responses in plants.

When insects and pathogens attack together, however, the plant's defensive decision-making becomes complicated. JA and SA pathways often work against each other, meaning that activating one defense response may weaken the other (Thaler *et al*., 2012). This trade-off creates a high-risk situation where one attacker can gain the upper hand. As a result, plant breeders and geneticists are now focusing on developing varieties that can mount strong, coordinated defenses against multiple biotic stresses at once.

The rapid growth of metabolomics, technology that examines the complete chemical profile of plants, has opened new opportunities to understand how these defense chemicals shift under dual stress conditions (Erb & Kliebenstein, 2020). By identifying metabolic markers linked to resilience, researchers aim to support more sustainable crop protection strategies. Ultimately, these insights can help farmers maintain yield stability even under rising pest and disease pressures.

2. Dual Attack Scenario in Crops

In many agricultural systems, insects and plant diseases do not act alone, rather, they often worsen each other's impact. When insects such as aphids, stem borers, or leafchewing pests feed on a plant, they create wounds that allow disease-causing fungi and bacteria to invade more easily, leading to more severe infections. On the other hand, once a pathogen infects a plant, it can change the plant's internal chemistry and the smell of its leaves, sometimes making the plant even more appealing to herbivores searching for food. Well-known examples include the whitefly-transmitted virus problems in tomato, maize attacked by borers alongside fungal rot, and the interaction between aphids and Sclerotinia in mustard and other Brassica crops. Together, these combined stresses speed up plant weakening, disrupt photosynthesis, and lead to major losses in crop productivity worldwide.

3. What is Plant Metabolomics

Metabolomics involves the comprehensive detection and measurement of small chemical compounds, known as metabolites, inside living organisms (Fiehn, 2002). In plants, these include essential primary metabolites such as sugars and amino acids, as well as a vast diversity of secondary metabolites that contribute to growth, defense, and signaling processes (Fernie & Tohge, 2017). When insects or pathogens attack, metabolomics enables researchers to track quick shifts in plant chemistry that cannot be observed through visible symptoms alone.

To map these biochemical changes, highly sensitive techniques like liquid chromatography-mass spectrometry (LC-MS), gas chromatography–mass spectrometry (GC-MS), and nuclear magnetic resonance (NMR) spectroscopy are commonly used (Patti *et al*., 2012). Comparing metabolic profiles of healthy versus stressed plants allows scientists to pinpoint specific molecules that indicate resistance or vulnerability.

By connecting genetic information with functional chemical responses, metabolomics strengthens our understanding of plant defense pathways. This knowledge helps plant breeders identify metabolites associated with tolerance to multiple biotic stresses, accelerating the development of varieties that can resist both insects and pathogens. In essence, metabolomics offers a powerful lens through which we can uncover the hidden biochemical strategies plants use to survive complex attacks.

4. Metabolomic Shifts During Dual Attack

When insects and pathogens attack together, plants undergo rapid metabolic reprogramming. Crosstalk between jasmonic acid (JA) and salicylic acid (SA) defense pathways can become antagonistic, weakening resistance to one of the attackers. Plants increase production of defensive metabolites like phenolics, terpenoids, alkaloids, and glucosinolates to deter herbivores and suppress pathogens. Dual stress also alters volatile organic compounds (VOCs), affecting attraction of natural enemies. Increased oxidative stress requires enhanced antioxidant metabolism for survival. These shifts determine plant tolerance or susceptibility. Field evaluations of insecticides against sap feeders demonstrate the strong metabolic costs plants endure under persistent pest pressure (Devi *et al*., 2024), supporting the need to study metabolomic shifts during dual attack.

5. Implications for Crop Protection

Understanding metabolomic shifts during dual attacks offers practical opportunities for improving crop health. First, these insights help breeders identify metabolic markers linked to multi-stress resistance, enabling the development of varieties with balanced JA-SA defenses. Second, metabolomics supports precision Integrated Pest Management (IPM) by revealing the best timing for pest and disease interventions, reducing unnecessary pesticide use.

Enhanced knowledge of plant volatiles allows the deployment of natural enemies more effectively in the field, strengthening biological control (Turlings & Erb, 2018). Dual stress studies also highlight the importance of beneficial microbes, such as plant growth-promoting rhizobacteria (PGPR) and endophytes, which can boost metabolic defenses and reduce disease severity (Backer *et al*., 2018).

For farmers, these strategies collectively translate into stronger crops and more sustainable yield protection under increasing pest and disease pressure driven by climate change. Thus, metabolomic research bridges scientific discovery with practical crop protection innovations, ensuring agricultural resilience in the future.

Conclusion

Plants facing simultaneous herbivore and pathogen attacks must rapidly reorganize their biochemical defenses. Dual attack disrupts the balance between jasmonic acid (JA) and salicylic acid (SA) signaling, often causing antagonism that weakens resistance to at least one threat. As shown through metabolomics research, plants adjust their production of secondary metabolites, volatile organic compounds, and antioxidants to cope with these complex conditions. However, this metabolic reprogramming is energy-intensive and frequently results in reduced growth and yield. With climate change increasing the frequency of overlapping pest and disease pressures, understanding these metabolomic shifts becomes crucial for developing future crop protection strategies. Insights from metabolomics are helping breeders identify biochemical markers linked to resilience and enabling better design of integrated pest and disease management practices. Ultimately, applying this knowledge will support more robust crop varieties and sustainable agricultural productivity worldwide.

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