

Plant Resilience: Multi-Omics and Systems Biology

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Abstract

Plants exhibit complex strategies to adapt to abiotic stresses. Integrated omics approaches, including metabolomics and proteogenomics, unravel system-level adaptations, metabolic reprogramming, and key signaling pathways like phytohormone crosstalk. Studies highlight the importance of redox signaling, epigenetic stress memory, and root system architecture in resilience. This comprehensive understanding, rooted in systems biology, reveals dynamic network interplay, offering vital insights into plant robustness under diverse environmental challenges. The findings are crucial for developing stress-tolerant crops.

Keywords

Plant stress; Abiotic stress; Omics; Metabolomics; Phytohormones; Epigenetics; Root system; Adaptation; Resilience; Systems biology

Introduction

Understanding how plants cope with challenging environmental conditions is paramount for ensuring agricultural productivity and ecosystem stability. Abiotic stresses, such as drought, salinity, and extreme temperatures, significantly impact plant growth and survival, prompting extensive research into the underlying mechanisms of adaptation and resilience. A major focus in this field involves deciphering the complex molecular, physiological, and morphological adjustments that plants make to mitigate stress.

One key area of investigation centers on metabolomics, a powerful tool for uncovering the metabolic fingerprints of stress resilience. This approach is crucial for identifying specific metabolites and dynamic metabolic shifts that occur when plants respond

to abiotic stresses, like drought or heat, thereby revealing key strategies for adaptation [1].

To gain a more holistic view of these intricate responses, integrated omics approaches are increasingly being advocated. Combining techniques such as genomics, transcriptomics, proteomics, and metabolomics allows researchers to capture a comprehensive picture of how plants react to environmental challenges. This integrated perspective is essential for developing crops with enhanced resilience [2].

Building on this, understanding plant adaptation to multiple stresses simultaneously, rather than isolated stressors, provides a more realistic insight into how plants survive in natural or agricultural settings. Multi-omics analyses are proving instrumental in dissecting these complex, system-level adjustments in response to combined environmental pressures, ultimately shedding light on overall plant resilience [3].

Beyond broad omics applications, specific regulatory mechanisms play critical roles. Phytohormones, for instance, are central to orchestrating plant stress responses. They engage in intricate

crosstalk networks, coordinating responses to various environmental challenges and facilitating adaptation through a complex web of signaling interactions [4].

Drought stress, a prevalent abiotic factor, induces profound changes in plant physiology. Research details specific metabolic reprogramming and associated signaling pathways that plants activate to cope with water scarcity. These adjustments in internal chemistry and communication are vital for survival and adaptation to dry conditions, offering crucial insights into drought tolerance mechanisms [5].

Similarly, in the context of heat stress, understanding adaptation involves integrated analyses of proteins and genes. Proteogenomics is employed to map system-level responses in crops like maize, illustrating how protein expression and modification contribute to resilience and how the entire plant system adapts to high temperatures [6].

From a broader perspective, plant resilience to abiotic stress is increasingly viewed through a systems biology lens. This approach emphasizes that robustness arises not from individual gene responses, but from the dynamic interplay of complex biological networks operating at multiple levels. It provides a holistic understanding of how plants maintain function under harsh conditions [7].

Cellular redox signaling is another fundamental aspect of plant stress management. This process is deeply intertwined with metabolic adjustments, enabling plants to sense and respond to stress effectively. Understanding the delicate balance and interplay between oxidants, antioxidants, and metabolic pathways is key to deciphering stress adaptation [8].

Intriguingly, plants possess a form of "memory" regarding past stress events. Epigenetic mechanisms, such as DNA methylation and histone modifications, are at the core of this plant stress memory. These mechanisms allow plants to adapt more effectively to recurring stressors, essentially enabling them to "learn" from past experiences [9].

Finally, the root system plays a critical, yet often overlooked, role in stress adaptation. Research underscores how both the physical architecture of roots and the metabolic changes occurring within them contribute significantly to a plant's ability to cope with environmental stresses. This highlights the importance of focusing on below-ground responses as crucial components of overall plant resilience [10].

Collectively, these studies emphasize that plant adaptation to

abiotic stress is a highly complex, integrated process involving molecular, metabolic, and systemic adjustments, governed by intricate signaling networks and influenced by environmental memory. These insights are fundamental for developing future strategies to enhance crop resilience in a changing climate.

Description

Plants face a continuous barrage of abiotic stresses, including drought, salinity, and extreme temperatures, which severely impact their growth and productivity. Research into how plants perceive, respond to, and ultimately adapt to these challenges is critical for improving crop resilience. A significant body of work focuses on comprehensive approaches, particularly the various 'omics' technologies, to dissect these intricate mechanisms. For example, metabolomics serves as a crucial tool for uncovering the metabolic fingerprints of stress resilience, identifying key metabolites and dynamic metabolic shifts under conditions like drought, salinity, and extreme temperatures [1]. The insights gained from metabolomics highlight how plants adjust their internal chemistry to survive.

Extending beyond single-omics approaches, the field increasingly recognizes the power of integrated omics. This involves combining genomics, transcriptomics, proteomics, and metabolomics to provide a holistic view of plant responses to environmental challenges. Such an integrated perspective is considered essential for paving the way to developing more resilient crops by understanding the "bigger picture" of stress responses [2]. Furthermore, plants in natural and agricultural settings rarely experience a single stress in isolation. Multi-omics analyses are therefore being employed to unravel the complex, system-level adjustments plants make in response to multiple simultaneous environmental pressures, offering a more realistic understanding of overall plant resilience [3]. This system-level adaptation is a key theme, revealing how interconnected pathways and processes contribute to survival.

The internal communication networks within plants are also central to stress management. Phytohormones, for instance, are critical signaling molecules that orchestrate plant defense and adaptation. Research emphasizes the intricate crosstalk between different phytohormones, revealing how they coordinate responses to various environmental challenges. This highlights that phytohormone signaling forms a complex network rather than a series of individual pathways, acting as a central hub for stress response and adaptation [4]. Specific stresses induce tailored responses. Drought stress, a major concern globally, leads to dramatic impacts on plant metabolism. Studies detail the specific metabolic reprogramming

and associated signaling pathways plants activate to cope with water scarcity, offering crucial insights into drought tolerance mechanisms through adjustments in internal chemistry and communication [5]. Similarly, when confronted with heat stress, understanding adaptation involves a close look at proteins and genes together. Proteogenomics reveals system-level adaptations in crops like maize to high temperatures, showing how protein expression and modification contribute significantly to resilience and how the entire system protects itself [6].

A systems biology perspective is essential for comprehending plant resilience to abiotic stress. This viewpoint emphasizes that robustness stems from the dynamic interplay of complex networks across multiple biological levels, rather than just individual gene responses. It provides a holistic understanding of how plants maintain function under harsh conditions and cope with adversity [7]. Another fundamental aspect is redox signaling, which is intricately linked with metabolic adjustments. This mechanism allows plants to sense and respond to stress by understanding the intricate dance between oxidants, antioxidants, and metabolic pathways in stress management [8]. Beyond immediate responses, plants exhibit a remarkable capacity for "stress memory." Epigenetic mechanisms, including DNA methylation and histone modifications, are explored as the basis for this memory, enabling plants to adapt more effectively to recurring stressors by "learning" from past experiences [9]. Lastly, the below-ground architecture plays an indispensable role. The root system is critical for stress adaptation, with both its physical architecture and the metabolic alterations within it contributing significantly to a plant's ability to cope with environmental stresses. This makes a strong case for focusing on root responses as crucial components of overall plant resilience and adaptation [10].

Conclusion

The provided articles collectively illuminate the multifaceted strategies plants employ to adapt and become resilient to abiotic stresses, like drought, salinity, and extreme temperatures. A central theme is the widespread application of 'omics' technologies, including metabolomics, genomics, transcriptomics, and proteomics, often integrated in multi-omics approaches, to gain a comprehensive understanding of plant responses at system levels. Metabolomics, for instance, is crucial for identifying key metabolites and dynamic metabolic shifts that underpin stress resilience. The importance of integrated omics extends to understanding broader plant stress responses, paving the way for more resilient crops, and dissecting system-level adjustments to multiple simultaneous stresses, reflecting real-world scenarios. Beyond molecular profiling, the role of

internal signaling networks is critical. Phytohormones are central regulators, coordinating intricate crosstalk networks to manage various environmental challenges and facilitate adaptation. Specific stresses, such as drought, trigger significant metabolic reprogramming and activate distinct signaling pathways, vital for survival. Similarly, heat stress responses involve proteogenomics to map system-level adaptations, highlighting how protein expression contributes to resilience. The papers also emphasize a systems biology perspective, viewing plant robustness not just as individual gene responses but as a dynamic interplay of complex networks across biological levels. Redox signaling is highlighted as a core component, intricately linked with metabolic adjustments for stress management. Furthermore, plants exhibit a remarkable "stress memory" mediated by epigenetic mechanisms, enabling more effective adaptation to recurring stressors. Lastly, the below-ground responses are vital, with root system architecture and metabolomic alterations within roots significantly contributing to a plant's overall ability to cope with environmental stresses. Collectively, these insights underscore the complex, integrated nature of plant adaptation mechanisms.

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