Hormonal Cross-Talk in Plants: Orchestrating Abiotic Stress Tolerance in a Changing Climate

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Plants, being sessile organisms, are constantly exposed to fluctuating environmental conditions that threaten their growth, productivity and survival. In recent years, cross-talk among different signalling molecules has emerged as a critical determinant of how plants perceive, integrate and respond to abiotic stresses such as drought, salinity, extreme temperatures and flooding. This understanding has gained particular importance in the context of global climate change, which is intensifying the frequency and severity of environmental stresses. At the same time, rapid population growth is placing unprecedented pressure on agricultural systems to produce more food of higher quality sustainably. Developing climate-resilient crops has therefore become one of the foremost challenges of modern agriculture. Meeting this challenge requires more than identifying single stress-tolerance genes or pathways. Instead, it demands a comprehensive understanding of the complex tradeoffs among interconnected signalling networks that regulate plant growth and stress responses. Among these networks, phytohormones play a central role. Acting as chemical messengers, plant hormones coordinate growth, development and adaptive responses by integrating environmental signals with internal physiological processes. Their interactions, both synergistic and antagonistic, form the backbone of plant resilience under dynamic environmental conditions.

Phytohormones as Central Regulators of Stress Responses

Plant growth and development are governed by a highly coordinated system of morphophysiological processes controlled by multiple genes and signaling cascades. Abiotic stress adaptation depends on sophisticated mechanisms of stress perception, signal transduction and downstream gene regulation. Phytohormones lie at the heart of these mechanisms, functioning as integrators that translate environmental cues into appropriate physiological responses. Major phytohormones involved in abiotic stress signalling include abscisic acid (ABA), auxin, brassinosteroids (BRs), cytokinins, ethylene and gibberellins (GAs). Each hormone contributes unique regulatory functions, yet none acts in isolation. Instead, their effects are shaped by extensive cross-talk, allowing plants to fine-tune responses depending on stress intensity, duration, developmental stage and tissue type. Understanding this hormonal interplay is essential for unravelling the complexity of plant stress tolerance.

Abscisic Acid: The Master Stress Hormone

Among all phytohormones, abscisic acid is widely recognized as the primary plant stress hormone. ABA plays a central role in regulating plant water status and mediating adaptive responses to drought, salinity, cold and mechanical injury. It is synthesized throughout the plant life cycle and is also involved in key developmental processes such as seed dormancy, germination and early seedling growth. Under water-deficit conditions, ABA accumulation triggers stomatal closure by acting on guard cells, thereby reducing transpiration and preventing excessive water loss. Beyond this localized effect, ABA also functions as a systemic signal, coordinating whole-plant responses to severe stress. Its rapid induction under a wide range of adverse conditions underscores its importance as a central regulator of abiotic stress tolerance. Moreover, ABA interacts extensively with other hormones, modulating growth–stress tradeoffs to ensure survival under unfavorable environments.

Auxin: Balancing Growth and Stress Adaptation

Auxin is a master regulator of plant growth, controlling cell division, elongation and differentiation. Its core functions are mediated through three interconnected processes: biosynthesis and metabolism, polar transport and signal transduction. Recent advances in biochemical, genetic, and structural studies have significantly improved our understanding of how auxin signalling interfaces with stress responses. In the context of abiotic stress, particularly drought, salinity, and temperature extremes, auxin plays a crucial role in shaping plant architecture and adaptive growth patterns. Stress-induced changes in auxin distribution and signalling can lead to characteristic morphological responses such as elongated hypocotyls, increased petiole length and angle and hyponastic growth. These adjustments help plants optimize light capture, reduce heat load, or improve water-use efficiency. Under heat stress, plants activate complex sensing and signalling mechanisms in which auxin interacts with other phytohormones to maintain growth and survival as temperatures rise. Thus, auxin acts as a key mediator that balances developmental processes with stress-induced growth modulation.

Brassinosteroids: Enhancing Growth and Stress Tolerance

Brassinosteroids are polyhydroxylated steroidal hormones that play essential roles in plant growth and development. Studies using BR-deficient or BR-insensitive mutants have demonstrated their importance in regulating cell expansion, vascular differentiation, leaf development, male fertility and senescence timing. Beyond development, BRs influence numerous metabolic pathways and regulate the expression of hundreds of genes involved in morphogenesis and stress adaptation. The agricultural potential of BRs has attracted considerable attention, particularly for their ability to enhance plant growth and yield under adverse conditions. Brassinosteroids have been shown to mitigate the detrimental effects of drought, salinity, extreme temperatures and heavy metal toxicity (including cadmium, copper, aluminium and nickel). By stabilizing membranes, enhancing antioxidant capacity, and modulating stress-responsive gene expression, BRs help maintain normal metabolic activity under stress. Their interaction with other hormonal pathways further amplifies their role in improving plant resilience.

Cytokinin: Integrating Development and Stress Responses

Cytokinin is key regulators of cell division and the cell cycle, originally identified as potent promoters of cytokinesis in tissue culture. In coordination with auxin, cytokinin maintains stem cell populations in shoot and roots apical meristems and regulates organ development. At the tissue level, they influence vascular differentiation, inhibit lateral root initiation, control light-mediated leaf expansion and delay leaf senescence. While the developmental roles of cytokinin are well established, their involvement in stress responses has only recently been elucidated. Cytokinin levels and signaling often decline under stress conditions, contributing to growth suppression and resource conservation. Their interaction with ABA is particularly important, as the balance between these hormones determines whether plants prioritize growth or stress survival. This dynamic interplay highlights the importance of cytokinin signalling in fine-tuning stress adaptation.

Ethylene: The Stress Signal Amplifier

Ethylene is a unique gaseous phytohormone involved in diverse aspects of plant growth and development, including fruit ripening, flower senescence and leaf and petal abscission. It also plays a prominent role in both biotic and abiotic stress responses. The concept of “stress ethylene” refers to the enhanced synthesis of ethylene triggered by environmental stressors such as temperature extremes, flooding, drought, high light, radiation, heavy metal and organic pollution, mechanical injury, insect attack, high salinity and pathogen infection. Ethylene often acts as a signal amplifier, modulating stress responses through interactions with ABA, auxin and other hormones. Depending on context, it can promote survival responses or accelerate senescence and abscission, thereby reducing metabolic demand under prolonged stress. Its dual role underscores the importance of hormonal balance in determining stress outcomes.

Gibberellins: Modulating Growth under Stress

Gibberellins are growth-promoting hormones increasingly recognized for their role in abiotic stress responses. Under unfavourable conditions such as cold, salinity and osmotic stress, reduced GA levels and signalling contribute to growth inhibition, allowing plants to conserve energy and resources. Conversely, enhanced GA biosynthesis and signalling promote rapid elongation growth during escape responses to shading or submergence. GA metabolism is tightly regulated at the transcriptional level, and recent studies have revealed interactions between the GA signalling regulator DELLA proteins and components of other hormonal pathways, including jasmonic acid signalling. These interactions provide additional layers of control through which GA signalling integrates multiple stress and developmental cues. As a result, GAs serve as prime targets for stress-induced growth modulation, either suppressing or promoting growth depending on environmental demands.

Conclusion

Hormonal cross-talk represents a central strategy by which plants integrate growth and stress responses in an ever-changing environment. Rather than acting independently, phytohormones form an intricate signalling network that balances survival and productivity under abiotic stress. Understanding the synergistic and antagonistic interactions among ABA, auxin, brassinosteroids, cytokinin, ethylene and gibberellins is crucial for deciphering the complexity of plant stress tolerance. As climate change continues to challenge global agriculture, insights into hormonal cross-talk offer promising avenues for developing stress-resilient crops. By targeting key hormonal pathways and their interactions, it may be possible to enhance crop performance without compromising growth or yield. Ultimately, harnessing the power of plant hormonal networks could play a vital role in addressing food security and sustainability in a rapidly changing world.

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