Ecofarming (e-Magazine)

Agriculture

Ecofarming
e-Magazine for Agriculture and Allied Sciences
http://www.ecofarming.rdagriculture.in
e-ISSN: 2583-0791

Role of Plant Hormones in Stress Response

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Received: July, 2025; Accepted: August, 2025; Published: October, 2025

Introduction

Plants, unlike animals, are immobile and constantly exposed to environmental fluctuations. These include abiotic stresses like drought, salinity, extreme temperatures, and heavy metals, as well as biotic stresses from pathogens and herbivores. To counter these threats, plants have evolved sophisticated hormonal signalling systems that regulate stress perception and responses. Plant hormones—also known as phytohormones—act as chemical messengers that mediate the adaptation to stress by modulating growth, gene expression, and metabolic pathways. Among the primary hormones involved are abscisic acid (ABA), ethylene, salicylic acid (SA), jasmonic acid (JA), auxins, gibberellins (GAs), cytokinins (CKs), brassinosteroids (BRs), and strigolactones (SLs). These hormones work both individually and in interaction with each other to provide tailored and often stress-specific responses.

Abscisic Acid: The Primary Hormone in Abiotic Stress Signalling

Among all phytohormones, abscisic acid (ABA) is the most closely associated with abiotic stress responses, particularly drought, salinity, and cold. Under water-deficient conditions, ABA biosynthesis increases rapidly, primarily in root tissues, followed by transport to leaves where it triggers stomatal closure to reduce transpiration (Cutler et al., 2010). ABA signalling involves the PYR/PYL/RCAR receptors, PP2C phosphatases, and SnRK2 kinases, forming a highly regulated module that activates ABA-responsive genes (Umezawa et al., 2010). These genes include those encoding for LEA proteins, osmoprotectants, and ROS-scavenging enzymes, which protect plant cells during dehydration and oxidative stress.

In salt stress, ABA plays a vital role in maintaining ion homeostasis by modulating ion transporters such as SOS1 and NHX1, and regulating osmolyte accumulation (Zhu, 2002). Moreover, ABA cross-talks with other hormones like ethylene and auxin to prioritize stress responses over growth processes.

Ethylene: A Hormone with Dual Roles in Stress Responses

Ethylene, a gaseous hormone, is involved in both abiotic (e.g., flooding, heat, hypoxia) and biotic (e.g., pathogen attack) stress responses. Under waterlogging, ethylene biosynthesis increases due to hypoxic conditions, which in turn activates ethylene response factors (ERFs) that mediate adaptations such as aerenchyma formation and internode elongation (Voesenek & Bailey-Serres, 2015). These adaptations help restore oxygen balance in submerged tissues.

Ethylene also contributes to biotic stress resistance through its synergistic interaction with JA. It activates the transcription of PR (pathogenesis-related) genes, chitinases, and glucanases that disrupt fungal cell walls (Broekaert et al., 2006). However, ethylene's effect is highly concentration-dependent. While moderate levels aid stress tolerance, excess ethylene can lead to leaf senescence and growth inhibition, especially during drought when it interacts antagonistically with ABA.

Salicylic Acid and Jasmonic Acid: Orchestrators of Biotic Stress Resistance

Salicylic acid (SA) is predominantly involved in resistance against biotrophic pathogens by triggering systemic acquired resistance (SAR) and local hypersensitive responses (HR). The NPR1 protein is a central regulator of SA signaling, activating PR genes that provide long-lasting immunity (Vlot et al., 2009). SA also primes plants for faster responses during subsequent infections.

Jasmonic acid (JA), on the other hand, is vital for defense against necrotrophic pathogens and insect herbivory. JA signaling depends on the COI1-JAZ-MYC2 pathway, which regulates secondary metabolite biosynthesis, such as alkaloids and terpenoids, that serve as chemical deterrents (Wasternack & Hause, 2013). JA levels increase rapidly in response to wounding or pathogen infection, enhancing the plant's ability to mount localized and systemic defenses. Importantly, SA and JA exhibit antagonistic interactions in many contexts, allowing the plant to fine-tune its response depending on the type of pathogen. For example, activation of SA can suppress JA-mediated insect defenses, and vice versa (Pieterse et al., 2012)

Auxins, Gibberellins, and Cytokinins in Stress Modulation

Traditionally categorized as growth-promoting hormones, auxins, gibberellins (GAs), and cytokinins (CKs) also contribute significantly to stress responses. Auxin regulates root architecture under stress conditions. During drought or salinity, auxin transport and distribution are altered, leading to enhanced lateral root growth and deeper rooting, which aid in water uptake (Kazan, 2013). Stress-responsive microRNAs (e.g., miR393) regulate auxin signalling by targeting auxin receptors like TIR1 (Navarro et al., 2006).

Gibberellins are usually downregulated during stress to conserve energy. The accumulation of DELLA proteins, which are negative regulators of GA signalling, enhances stress tolerance by promoting ROS detoxification, modulating transcription factors, and interacting with JA and ABA pathways (Achard et al., 2008). DELLA proteins function as central integrators of growth repression and defense activation under stress.

Cytokinins, which delay senescence and promote cell division, exhibit varied responses under stress. In drought, CK levels typically decline, but exogenous CK application can delay leaf senescence and boost antioxidant capacity, enhancing drought tolerance (Ha et al., 2012). However, a delicate balance is required, as high CK levels under stress can sometimes hinder adaptive responses.

Brassinosteroids and Strigolactones: Emerging Hormones in Stress Defense

Brassinosteroids (BRs), although best known for promoting cell elongation and vascular differentiation, also play pivotal roles in stress tolerance. BRs increase resistance to heat, cold, drought, and salinity by enhancing photosynthetic efficiency, antioxidant enzyme activities, and membrane stability (Divi et al., 2010). Transcription factors like BZR1 and BES1, regulated by BRs, influence both growth and defense-related gene expression.

Strigolactones (SLs), initially recognized for regulating shoot branching and root symbioses, are now being appreciated for their role in abiotic stress adaptation. SLs promote root elongation, reduce stomatal conductance, and enhance symbiotic interactions with arbuscular mycorrhizal fungi, facilitating better water and nutrient uptake during drought (Mostofa et al., 2018). Their interaction with ABA and ethylene further highlights their integrative function in stress signaling.

Hormonal Cross-Talk and Network Complexity

One of the most remarkable features of plant hormone signalling is the cross-talk among different hormones, creating a dynamic and context-dependent regulatory network. Rather than acting in isolation, hormones integrate their signals to balance growth and stress adaptation. For instance, ABA and ethylene can act antagonistically in seed germination but synergistically in drought stress responses (Fujita et al., 2006). Similarly, auxin signalling can be modulated by ABA during drought to redirect root growth.

Cross-talk is mediated by shared transcription factors (e.g., WRKY, MYB, NAC), protein kinases, and microRNAs that serve as convergence points for multiple hormone pathways. This integration enables plants to prioritize defenses, allocate resources efficiently, and fine-tune developmental programs under combined stresses.

The spatial and temporal dynamics of hormone accumulation and sensitivity add further complexity. For example, localized production of SA at infection sites versus systemic spread of JA allows compartmentalized defense responses. Modern tools like transcriptomics, proteomics, and biosensors are now being used to decode these intricate signalling webs.

Biotechnological Applications and Future Directions

Understanding hormone-regulated stress responses has immense potential in agriculture and crop biotechnology. Genetic engineering approaches that manipulate hormone biosynthesis or signalling have led to improved drought and disease resistance. For example, overexpression of ABA biosynthetic genes like NCED3 enhances drought tolerance in Arabidopsis and rice (Iuchi et al., 2001). Similarly, suppression of ethylene biosynthesis in tomato improves tolerance to flooding (Ciardi & Klee, 2001).

CRISPR/Cas9 gene editing is enabling precise manipulation of hormone-related genes, while synthetic hormone analogs and plant growth regulators are being explored as foliar sprays to enhance resilience. Furthermore, hormone-responsive promoters are being used in transgenic crops to drive stress-inducible gene expression only under specific conditions, reducing energy costs during normal growth.

Looking ahead, more emphasis needs to be placed on multi-stress combinations, which are more reflective of natural environments. Climate change is likely to result in concurrent stresses, making it essential to engineer plants with broad-spectrum resistance regulated through hormonal networks.

Conclusion

Plant hormones act as central regulators in orchestrating responses to diverse stresses. Through a complex web of interactions, hormones such as ABA, ethylene, SA, JA, auxins, GAs, CKs, BRs, and SLs enable plants to sense environmental threats, reprogram gene expression, modulate development, and optimize resource use. Their ability to act individually and synergistically equips plants with a flexible and adaptive stress response system. As environmental challenges intensify, integrating hormonal knowledge into crop breeding and biotechnology will be critical for achieving sustainable and resilient agriculture.

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