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Hormone Mediated Root Architecture for Abiotic Stress Tolerance in Plants

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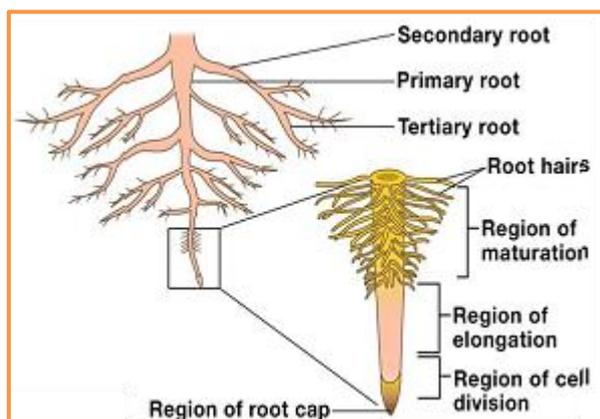
Plants face constant challenges from abiotic stresses such as drought, salinity, flooding and heavy metal toxicity, yet their survival strategies largely remain hidden beneath the soil. Root system architecture (RSA) plays a central role in helping plants sense stress and adapt to hostile environments. This dynamic underground network is finely regulated by plant hormones including auxin, abscisic acid, cytokinin, ethylene, jasmonic acid and brassinosteroids. Through intricate hormonal crosstalk, roots alter their depth, branching pattern, growth direction and physiological activity to optimize water and nutrient uptake while minimizing stress damage. Hormone-mediated RSA also coordinates whole-plant responses by transmitting stress signals from roots to shoots, influencing photosynthesis, stomatal behavior and growth. These adaptations involve physiological, biochemical, molecular and morphological changes that together enhance plant resilience. Understanding how hormones shape root behavior opens new opportunities for developing climate-resilient crops with improved productivity, sustainability and resource-use efficiency in a changing environment.

Introduction

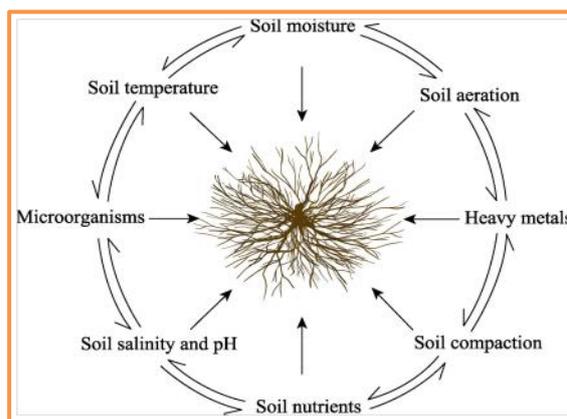
Hormone-mediated root architecture (RSA) refers to the complex regulation of root growth and development by plant hormones, which act as signaling molecules controlling cell proliferation, differentiation, and branching. The interaction between hormones and reactive oxygen species (ROS) plays a key role in enhancing nutrient uptake, stress tolerance, and overall agricultural productivity. RSA, defined as the spatial configuration of the root system, is a crucial agronomic trait influencing plant growth, yield, and adaptability. Hormonal pathways regulate RSA plasticity, enabling roots to respond dynamically to environmental cues, while abiotic stresses such as heat, cold, drought, salinity, flooding, and metal toxicity modify root anatomy and guide roots toward favourable conditions and away from stress.

The Hidden Story Beneath the Soil

Plants surviving under drought, salinity or flooding our attention usually goes to leaves, flowers or grains. But the real battle for survival happens underground. Roots are not just anchors that hold plants in place - they are intelligent, dynamic organs that sense stress and reshape themselves to help plants survive harsh environments. At the heart of this underground adaptability lies a powerful regulator: plant hormones.



Components of root system architecture



Factors affecting RSA

Roots: The First Responders to Stress

The arrangement and structure of roots, known as **root system architecture (RSA)**, determine how effectively a plant can absorb water, nutrients and oxygen. RSA is highly plastic, meaning it can change shape depending on environmental conditions such as drought, salinity, flooding or heavy metal contamination (Jung & McCouch, 2013; Karlova *et al.*, 2021). This flexibility allows roots to grow deeper during drought, avoid saline patches in soil or form air spaces when oxygen is limited.

Hormones: The Master Controllers of Root Growth

Plant hormones act as chemical messengers that regulate every stage of root development - from cell division to root hair formation. Among them, **auxin** is the central regulator, controlling primary root elongation, lateral root formation and root hair development (Li *et al.*, 2022). Other hormones fine-tune this process:

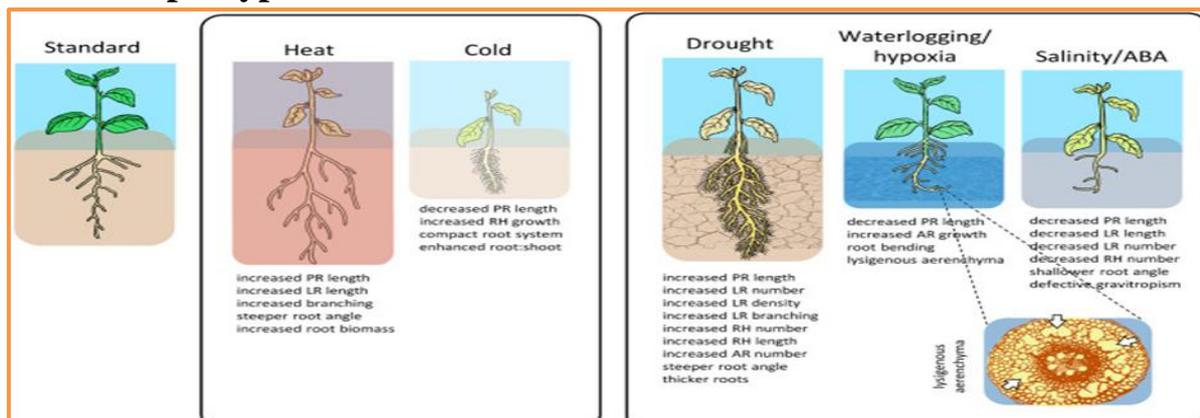
- **Cytokinins** generally suppress excessive root elongation and balance root–shoot growth
- **Abscisic acid (ABA)** helps roots survive stress by promoting deeper rooting and conserving resources
- **Ethylene** modifies root plasticity, especially under flooding and waterlogging
- **Brassinosteroids, jasmonic acid and strigolactones** further shape root branching and stress responses (Singh *et al.*, 2024)

These hormones do not act alone—they constantly interact through a complex network known as hormonal crosstalk, ensuring roots respond precisely to changing environments.

Communication of roots in stress to the Whole Plant

Roots are also major signaling hubs. When they experience stress, they send messages to shoots using hormones, reactive oxygen species (ROS), calcium ions and mobile peptides through the vascular system (Yadav *et al.*, 2025). These signals help regulate stomatal closure, water use efficiency and overall plant metabolism, allowing the entire plant to adjust to stress conditions.

Plant morphotypes in various abiotic stress conditions



Hormonal Control of Roots Under Drought

Drought is one of the most damaging abiotic stresses to crops. Under water deficit conditions, ABA plays a dominant role by promoting deeper primary root growth while suppressing unnecessary lateral roots, helping plants access deeper soil moisture (Margay *et al.*, 2024). Auxin redistribution, rather than increased production, further supports drought-adaptive root growth. Reduced cytokinin and gibberellin activity prevents excessive growth and conserves energy during stress.

Salinity: Hormonal Regulation of Root Adaptive Responses to Salt Stress

Salinity stress forces root to change direction and structure. This phenomenon, called halotropism, is driven by asymmetric auxin distribution that directs roots away from high salt zones (Yun *et al.*, 2024). Hormones such as ABA and salicylic acid help maintain ion balance by regulating sodium and potassium transport, while jasmonic acid and brassinosteroids strengthen antioxidant defenses and protect root cells from oxidative damage (Xiao & Zhou, 2023).

Hormonal Regulation of Roots Under Heavy Metal Stress

Heavy metals disrupt normal root growth by interfering with hormone transport and signaling. Auxin gradients are disturbed, leading to reduced root elongation, while elevated ABA and ethylene levels slow growth but enhance stress tolerance (Rahman *et al.*, 2023). Brassinosteroids help maintain root meristem activity, and jasmonic acid activates detoxification pathways, allowing plants to survive in contaminated soils (Jalmi *et al.*, 2018).

Hormonal Regulation of Roots under water logging stress

ethylene dramatically improves waterlogging tolerance by reshaping root architecture. Ethylene treatment will enhance lateral root formation, increase root surface area and promote aerenchyma formation - air-filled spaces that allow oxygen transport in flooded soils (Geng *et al.*, 2023). Plants with higher endogenous ethylene levels show better survival, reduced oxidative damage and improved root integrity under waterlogged conditions.

Genes, Hormones and the Future of Climate-Resilient Crops

Modern research has identified several genes that work alongside hormones to regulate RSA under stress, such as **AUX1**, **PIN transporters**, **DRO1** and **ABI1**, which control root depth, angle and branching (Justamante *et al.*, 2025). Understanding how these genes interact with hormones opens new possibilities for breeding climate-resilient crops.

Responses of plant to Abiotic Stress

Physiological responses

- ❖ Recognition of root signal
- ❖ Loss of turgor and osmotic adjustment
- ❖ Transient decrease in photochemical efficiency
- ❖ Reduced leaf water potential
- ❖ Decreased in stomatal conductance to CO₂
- ❖ Reduced internal CO₂ concentration, decline in net photosynthesis
- ❖ Reduced peduncle elongation and spikelet sterility
- ❖ Reduced pollen–pistil interaction
- ❖ Reduced growth rate and crop yield

Biochemical responses

- ❖ Alteration in redox homeostasis and ionic balance
- ❖ Osmolyte (proline, glycine betaine, sorbitol, mannitol, etc.) biosynthesis
- ❖ ROS metabolism (¹O₂, O₂^{•-}, OH⁻, H₂O₂ etc.)
- ❖ Oxidation of lipids (MDA) and proteins (carbonyl compounds, etc.)
- ❖ Antioxidant function

Enzymes: CAT, SOD, POX, GR, APX, etc.

Non-enzymes: Ascorbate (Asc), GSH, tocopherol, carotenoids, phenolics & other secondary metabolites

Molecular responses

- ❖ Signal perception and transduction via MAPKs, Ca²⁺, etc.
- ❖ Increased expression of drought stress responsive and ABA biosynthetic genes
- ❖ Expression of ABA and dehydrin responsive genes
- ❖ Synthesis of specific proteins like LEA, dehydrin, aquaporin, DSPs, etc.
- ❖ Drought stress tolerance

Morphological responses

- ❖ Reduction in depth, distribution, number, and length of primary roots
- ❖ Reduction in root and shoot length
- ❖ Leaf rolling, curling, leaf area reduction & wilting
- ❖ Decreased plant biomass and growth inhibition
- ❖ Reduction in flowering and fruiting leading to decreased crop yield

Future thrust

Understand different hormone crosstalk networks (auxin, ABA, cytokinin, ethylene) controlling root plasticity for better application in abiotic stresses. Understand hormone–environment sensing driving hydrotropism, halotropism and nutrient foraging. Identifying stress-responsive genetic and epigenetic regulators of hormone pathways for better utilization. Explore hormone- root microbiome interactions enhancing stress resilience. Convert discoveries to crop-specific root ideotypes for drought, salinity and nutrient stress. Applying advanced tools (biosensors, single-cell omics, CRISPR, root phenotyping). Biotechnological approaches for climate-resilient, energy-efficient root systems under combined stresses.

Conclusion

Hormone-mediated root system architecture (RSA) plays a pivotal role in plant adaptation to abiotic stresses. Phytohormones regulate root growth, branching and plasticity through complex crosstalk and signaling networks. Studying synergistic and antagonistic interactions among hormones ensure balanced root growth for better adaptability and stress tolerance. Stress-induced hormonal modulation enables optimized root architecture by maintaining ion homeostasis, regulating ROS balance and activating stress-responsive genes in abiotic stress conditions. Understanding these integrated hormonal and molecular controls of RSA provides valuable opportunities for developing climate-resilient crops with improved stress tolerance and resource-use efficiency

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