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# The Role of Phytohormones in Regulating Plant Growth and Development under Climate Change Scenarios

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***Abstract***

*Climate change poses a significant threat to global agriculture, affecting plant growth, development, and productivity. Phytohormones—such as auxins, gibberellins, cytokinins, abscisic acid, ethylene, salicylic acid, and jasmonic acid—play pivotal roles in helping plants adapt to environmental stresses induced by climate change, including temperature fluctuations, drought, salinity, and elevated* $CO_2$ *levels. This review synthesizes recent advancements in understanding how phytohormones regulate key physiological and molecular responses under these stress conditions. We highlight the cross-talk among hormone signaling pathways that orchestrate growth-defense trade-offs, stress memory, and resilience. Furthermore, the integration of hormone biosynthesis and signaling with modern biotechnological approaches, such as gene editing and transcriptome profiling, is discussed in the context of developing climate-resilient crops. By elucidating the central role of phytohormones in stress adaptation, this review provides a foundation for future strategies aimed at enhancing crop productivity and sustainability in the face of a changing climate.*

***Keywords:*** *Phytohormones, climate change, plant growth, hormonal signaling, abiotic stress, drought, salinity, temperature stress, stress tolerance*

## 1. Introduction

Global climate change represents one of the most pressing challenges to agriculture and food security in the 21st century. Driven by increased greenhouse gas emissions, it manifests through rising global temperatures, erratic precipitation patterns, prolonged droughts, floods, and increased incidence of extreme weather events [1]. These environmental changes have a profound influence on plant growth, development, and overall productivity. Plants, being sessile organisms, cannot escape from adverse conditions and have thus evolved intricate signaling pathways to perceive and respond to external stimuli. Among these pathways, hormonal regulation through phytohormones plays a central role in facilitating plant adaptation and resilience [2-3].

Phytohormones, often referred to as plant hormones, are small organic molecules produced in minute quantities that regulate a wide range of physiological processes. These include cell division, elongation, differentiation, flowering, fruiting, seed germination, senescence, and responses to biotic and abiotic stresses. The primary phytohormones include auxins, gibberellins, cytokinins, abscisic acid (ABA), ethylene, jasmonates, salicylic acid, brassinosteroids, and strigolactones. In the face of climate change, these hormones do not act in isolation but interact with each other in complex networks known as hormonal cross-talk to orchestrate adaptive responses [4]. Temperature stress, both in terms of heat and cold, is one of the most direct impacts of climate change. Elevated temperatures can disrupt enzymatic functions, membrane stability, and reproductive development, leading to reduced yields. Phytohormones like salicylic acid and ethylene play crucial roles in heat stress tolerance, while abscisic acid is involved in cold stress responses. Through hormonal modulation, plants can initiate protective responses such as the expression of heat shock proteins or the accumulation of osmoprotectants.

Drought, a major consequence of altered rainfall patterns, causes osmotic stress and disrupts water relations within plants. One of the most well-studied hormones in drought tolerance is abscisic acid. ABA levels rise rapidly in response to drought, leading to stomatal closure to minimize water loss, activation of drought-responsive genes, and synthesis of protective proteins. Similarly, cytokinins, which typically promote cell division and shoot growth, are suppressed under drought conditions to conserve energy and resources, demonstrating a clear hormonal shift during water scarcity [5-6]. Flooding or waterlogging, which reduces oxygen availability in the root zone, is another major stress factor. Ethylene, known for its role in senescence and fruit ripening, also mediates responses to flooding by promoting the formation of aerenchyma (air spaces in roots) and adventitious roots to enhance oxygen uptake. Gibberellins, which promote growth, may be downregulated under such stress to limit elongation that could otherwise be detrimental under hypoxic conditions [7].

Salinity stress, increasingly observed in coastal and irrigated agricultural lands due to seawater intrusion and improper water management, affects ionic and osmotic balance. Phytohormones such as ABA, jasmonic acid, and salicylic acid coordinate the activation of ion transporters, antioxidant enzymes, and protective metabolites under saline conditions. Auxins and cytokinins may also reprogram root architecture to optimize water and nutrient uptake under stress [8-9]. Beyond individual stress responses, phytohormones are integral to developmental reprogramming under combined or sequential stress conditions—a likely scenario under ongoing climate change. For instance, auxin distribution can be altered by temperature and light changes, impacting tropisms and developmental patterns. Cross-talk between hormones enables fine-tuning of growth-defense trade-offs, ensuring that the plant allocates resources efficiently depending on the nature and severity of the stress encountered [10]. Recent advances in molecular biology, transcriptomics, and genome editing tools such as CRISPR/Cas9 have enabled researchers to manipulate hormone biosynthesis and signaling pathways. By overexpressing or silencing key hormonal genes, scientists can engineer crops with improved stress tolerance and growth performance under climate-stressed conditions. For example, enhancing ABA biosynthesis genes has led to drought-tolerant varieties, while altering ethylene signaling has improved flooding tolerance in some rice cultivars.

Another layer of complexity is added by the interaction between phytohormones and environmental cues mediated through epigenetic regulation, non-coding RNAs, and microbial signaling. Root-associated microbes such as rhizobacteria can modulate hormonal levels and responses, contributing to plant stress tolerance [11]. This opens up opportunities for sustainable agricultural interventions such as biofertilizers and plant growth-promoting rhizobacteria (PGPRs) that enhance hormonal efficiency in stressed environments, phytohormones serve as vital regulators of plant development and survival under the ever-changing environmental conditions driven by climate change. Understanding their complex signaling networks and interactions provides a foundation for designing climate-resilient crops. This review aims to explore the dynamic roles of key phytohormones under various climate-induced stresses, their synergistic and antagonistic interactions, recent research insights, and potential applications in sustainable agriculture and crop improvement programs [12]. A comprehensive understanding of these mechanisms is indispensable for addressing the multifaceted challenges posed by climate change to global food security.


**Fig 1: The morphological, physiological, and biochemical response of a plant under salinity stress.** Under salinity stress, plants exhibit a range of morphological changes such as reduced shoot and root growth, leaf curling, and premature senescence. Physiologically, salt stress leads to stomatal closure, decreased photosynthesis, and disrupted water and ion homeostasis. Biochemically, plants respond by accumulating osmoprotectants (like proline), antioxidants, and stress-related proteins. Elevated levels of reactive oxygen species (ROS) trigger antioxidative defense mechanisms. These responses collectively aim to enhance plant tolerance and maintain cellular integrity under saline conditions copyright from MDPI and ref paper [8].

## 2. Overview of Major Phytohormones and Their Functions

Phytohormones, also known as plant hormones, are naturally occurring organic compounds that exert profound effects on plant physiological processes at very low concentrations. These molecules function as chemical messengers, enabling plants to coordinate their growth, development, and responses to environmental stimuli [13]. Phytohormones are synthesized in specific plant tissues but often act at sites distant from their origin, demonstrating a high degree of spatial and temporal control. Each class of phytohormone is associated with distinct roles in plant biology, although their effects often overlap due to synergistic or antagonistic interactions. Below is a comprehensive overview of the major phytohormones and their primary functions:

**Auxins**
Auxins, such as indole-3-acetic acid (IAA), are primarily synthesized in shoot apices and young leaves [14]. They are central regulators of:
• **Cell elongation**: Auxins promote cell wall loosening and turgor-driven expansion, crucial for stem and root growth.

• **Apical dominance**: High auxin levels at the shoot tip suppress lateral bud growth, directing energy towards vertical elongation.

• **Root initiation and development**: Auxins induce lateral and adventitious root formation, especially during vegetative propagation.

• **Phototropism and gravitropism**: By redistributing auxin in response to light and gravity, plants can orient themselves for optimal resource capture.

**Gibberellins (GAs)**
Gibberellins are a large family of diterpenoid acids involved in various developmental processes:
• **Stem elongation**: GAs promote internodal elongation, often through stimulating cell division and elongation.

• **Seed germination**: They counteract ABA effects and trigger the production of hydrolytic enzymes that mobilize stored nutrients.

• **Flowering induction and fruit development**: GAs play a role in the transition from vegetative to reproductive growth in some plants and influence fruit set and growth.

**Cytokinins**
Cytokinins are adenine derivatives synthesized in roots and transported to aerial parts, with key roles including:
• **Cell division and organogenesis**: Cytokinins are essential for cytokinesis and are widely used in tissue culture.

• **Delay of leaf senescence**: They maintain chlorophyll content and photosynthetic capacity.

• **Nutrient mobilization**: Cytokinins enhance source-sink relationships, improving nutrient allocation.

• **Shoot initiation**: In contrast to auxins, cytokinins promote shoot formation in vitro.

**Abscisic Acid (ABA)**
Often referred to as the "stress hormone," ABA is a key mediator of plant responses to abiotic stress:
• **Stomatal closure**: ABA induces guard cell shrinkage, reducing water loss during drought.

• **Seed dormancy**: It prevents premature germination, particularly under unfavorable conditions.

• **Stress tolerance**: ABA activates stress-responsive genes and pathways to help plants survive salinity, drought, and freezing conditions.

**Ethylene**
Ethylene is a gaseous hormone involved in:
• **Fruit ripening**: It regulates softening, coloration, and sugar accumulation in climacteric fruits.

• **Leaf and petal abscission**: Ethylene promotes senescence and abscission processes.

• **Stress responses**: It modulates responses to biotic and abiotic stresses, including pathogen attack, mechanical damage, and flooding.

**Salicylic Acid (SA)**
Salicylic acid is a phenolic compound central to plant immunity:
• **Systemic Acquired Resistance (SAR)**: SA initiates long-lasting defense mechanisms following local pathogen exposure.

• **Pathogenesis-Related (PR) proteins**: It induces the expression of PR genes that protect against microbial invaders.

• **Abiotic stress tolerance**: SA has roles in mitigating oxidative stress and enhancing heat and salt tolerance.

**Jasmonates (JAs)**
Derived from linolenic acid, jasmonates are involved in:
• **Defense against herbivores and necrotrophic pathogens**: JAs activate production of secondary metabolites and proteinase inhibitors.

• **Wound responses**: JAs rapidly accumulate following mechanical damage to coordinate healing and defense.

• **Reproductive development**: They are implicated in flower development and fertility.

**Brassinosteroids (BRs)**
BRs are polyhydroxysteroids that regulate:
• **Cell expansion and elongation**: BRs promote cell wall loosening and growth.

• **Vascular differentiation**: They influence xylem and phloem patterning during organogenesis.

• **Stress responses**: BRs enhance tolerance to temperature extremes, drought, and heavy metals by modulating antioxidant activity.

**Strigolactones**
Strigolactones are carotenoid-derived hormones recognized for:

- **Regulation of shoot branching**: They inhibit axillary bud outgrowth, maintaining apical dominance.

- **Root architecture modulation**: Strigolactones promote deeper rooting and interaction with mycorrhizal fungi.

- **Seed germination**: They play roles in the germination of parasitic plants, which has ecological implications.

Together, these phytohormones create a tightly interconnected signaling network that allows plants to integrate developmental cues with environmental signals. This network becomes even more crucial under the erratic and challenging conditions imposed by climate change. Understanding these hormonal mechanisms provides insights into how plants maintain resilience and offers potential targets for developing climate-smart crops through breeding and biotechnological interventions [15].

3. Hormonal Responses to Climate-Induced Abiotic Stresses
Climate change introduces a spectrum of abiotic stresses—including drought, heat, cold, and salinity—that directly impact plant growth, development, and productivity. Phytohormones act as central regulators in the plant's adaptive response to these environmental fluctuations. By modulating various physiological and molecular processes, hormones help plants survive adverse conditions [16]. Each stressor elicits specific hormonal responses, often involving intricate crosstalk among multiple signaling pathways.

***Drought Stress***
Drought is one of the most critical constraints on crop productivity. Under drought conditions, abscisic acid (ABA) becomes the dominant phytohormone, orchestrating the plant's defense. ABA accumulation triggers stomatal closure, reducing water loss through transpiration. This action is facilitated by ABA-mediated activation of ion channels in guard cells, which leads to decreased stomatal aperture. Furthermore, ABA induces the biosynthesis of osmoprotectants like proline, sugars, and other compatible solutes that help maintain cell turgor. It also regulates the expression of drought-responsive genes such as dehydrins and late embryogenesis abundant (LEA) proteins, which stabilize membranes and proteins. In addition to ABA, jasmonates (JAs), salicylic acid (SA), and brassinosteroids (BRs) interact to modulate stress tolerance [17]. For example, SA plays a role in reducing oxidative damage by enhancing antioxidant enzyme activity, while BRs enhance drought resilience by regulating photosynthesis and cell wall remodeling.

***Heat Stress***
Heat stress alters hormonal balance and disrupts growth and development. Ethylene and salicylic acid are key players in the heat stress response. Both hormones regulate the expression of heat shock proteins (HSPs), which act as molecular chaperones stabilizing proteins under elevated temperatures. Ethylene production increases under heat stress, triggering downstream transcriptional changes that enhance stress tolerance. At the same time, auxin transport and signaling are disrupted, leading to impaired root elongation and shoot architecture. ABA also contributes to heat stress mitigation by regulating stomatal behavior and promoting osmoprotection. Cytokinins, on the other hand, are known to delay heat-induced senescence and maintain chlorophyll content, thereby supporting photosynthetic efficiency [18]. Together, these hormonal pathways enable the plant to maintain metabolic homeostasis and recover from thermal stress.

***Cold Stress***
Low temperature stress, particularly chilling and freezing, is a major limiting factor for plant distribution and yield in temperate regions. In response to cold, ABA and JAs accumulate significantly. These hormones contribute to cold acclimation by regulating genes involved in membrane stability, cryoprotectant accumulation, and antioxidant defense. A central player in cold stress response is the CBF (C-repeat binding factor) family of transcription factors. ABA signaling promotes the expression of CBFs, which in turn activate a suite of cold-responsive (COR) genes [19]. Ethylene also has a complex role in cold stress: while it may accelerate senescence in some species, it can also enhance cold tolerance through ROS detoxification and gene activation. Crosstalk between ABA, JA, and ethylene fine-tunes the stress response to ensure that growth suppression is balanced with adequate protection mechanisms.

***Salinity Stress***
Salt stress is another widespread abiotic challenge that leads to ionic toxicity and osmotic imbalance. ABA is once again central to the adaptive response, mediating stomatal closure, ion homeostasis, and activation of salt stress-responsive genes. ABA also promotes the expression of transporters involved in $Na^+$ sequestration and selective $K^+$ uptake, crucial for maintaining ionic balance. Cytokinins, in contrast, often act antagonistically under saline conditions. Their suppression helps conserve energy and limit unnecessary growth during stress periods. Gibberellins (GAs) are also downregulated, as their growth-promoting effects could be detrimental under salt stress. Ethylene plays a dual role—it can inhibit root elongation under high concentrations but also enhance root branching and stress tolerance in certain contexts [20]. Brassinosteroids (BRs) mitigate salinity damage by enhancing antioxidant defenses and stabilizing cellular membranes. Moreover, JAs and SA further contribute to salt stress tolerance by modulating oxidative stress and regulating gene expression associated with detoxification.

**4. Hormonal Crosstalk and Synergistic Interactions**

Phytohormones rarely function in isolation; instead, their signaling pathways often overlap and interact in complex networks that coordinate plant growth, development, and stress responses. This hormonal crosstalk can be synergistic, where hormones work together to enhance a particular physiological outcome, or antagonistic, where one hormone suppresses the action of another. For instance, abscisic acid (ABA) and ethylene can either cooperate or antagonize depending on the nature and duration of the stress. In drought stress, ABA promotes stomatal closure, but elevated ethylene levels can counteract this effect, promoting stomatal reopening and possibly accelerating senescence. Conversely, both ABA and ethylene jointly activate certain stress-responsive genes during pathogen attack or abiotic stress [21]. Brassinosteroids (BRs) positively interact with auxins by enhancing auxin signaling and transport, leading to improved cell elongation and vascular development. On the other hand, salicylic acid (SA) and jasmonic acid (JA) often exhibit antagonistic roles in biotic stress responses—SA predominantly mediates defense against biotrophic pathogens, whereas JA is more effective against necrotrophs and herbivores. Understanding these interactions is crucial for designing strategies to fine-tune hormonal responses in crops for improved resilience to multiple stresses.

**5. Genetic and Molecular Insights**

Recent breakthroughs in molecular biology and functional genomics have significantly expanded our understanding of the genes, receptors, and signaling components involved in phytohormone-mediated responses. High-throughput technologies such as RNA sequencing (RNA-Seq) and microarrays have identified hundreds of hormone-responsive genes, revealing their temporal and spatial expression under stress conditions [22]. Key transcription factors like DREB (Dehydration-Responsive Element-Binding), AREB/ABF (ABA-Responsive Element Binding Protein), and MYC/MYB families have emerged as central regulators in hormonal signaling cascades. Additionally, hormone receptors such as PYR/PYL/RCARs (for ABA), GID1 (for gibberellins), and TIR1/AFB (for auxin) have been characterized at the structural and functional levels. Modern genome editing tools such as CRISPR-Cas9 and RNA interference (RNAi) have enabled precise manipulation of genes involved in hormone biosynthesis, signaling, and transport. For example, knocking out negative regulators of ABA signaling has been shown to enhance drought tolerance in several crops. Likewise, overexpression of ethylene-insensitive transcription factors has led to improved tolerance to salinity and oxidative stress. These genetic tools are paving the way for tailoring hormone responses to specific stress environments.

**6. Biotechnological Applications and Future Prospects**

Harnessing the regulatory power of phytohormones through biotechnological approaches holds great promise for improving crop resilience in the face of climate change. Transgenic plants engineered to overexpress hormone biosynthetic genes—such as AtNCED3 for ABA or YUC genes for auxin—demonstrate enhanced tolerance to drought, heat, and salinity. The exogenous application of hormone analogs or synthetic regulators is also being explored to modulate hormonal responses without altering the genome [23]. Furthermore, plant growth-promoting rhizobacteria (PGPR) that produce phytohormones like indole-3-acetic acid (IAA) and gibberellins are gaining traction as bioinoculants for sustainable stress management. In the realm of crop improvement, precision agriculture is integrating phytohormone profiling and phenomics to select genotypes with optimal hormone responses [24-25]. Smart breeding techniques using marker-assisted selection (MAS) based on hormone-responsive genes are accelerating the development of climate-resilient cultivars. Looking forward, combining multi-omics platforms, machine learning, and synthetic biology could revolutionize our ability to predict and engineer plant responses to complex environmental stresses through the lens of phytohormone networks [26].

**7. Conclusion**

In the face of escalating climate change and its profound impacts on agricultural systems, understanding the intricate roles of phytohormones has become more critical than ever. Phytohormones serve as key regulators that orchestrate plant growth, development, and adaptive responses to a wide range of abiotic stresses such as drought, salinity, heat, and cold. The dynamic crosstalk and synergistic or antagonistic interactions among these hormones enable plants to fine-tune their physiological and molecular processes to survive under fluctuating environmental conditions. Advancements in molecular biology, genetics, and biotechnology have unveiled the complexity of hormonal signaling networks and provided powerful tools to manipulate them for improving crop resilience. Genetic engineering, hormone analog applications, and precision breeding strategies that target hormonal pathways offer promising avenues for developing climate-resilient crops, a holistic and integrative approach that combines traditional breeding, modern biotechnological tools, and sustainable agricultural practices is necessary to fully exploit the potential of phytohormone-based interventions.

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