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# Hormonal regulatory mechanisms during seedlings establishment

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***Abstract:*** *Seedling establishment is a critical developmental stage in the plant life cycle, marking the transition from heterotrophic to autotrophic growth. It encompasses a coordinated physiological process involving seed germination, root breakthrough, hypocotyl elongation, cotyledon expansion, and the construction of the primary photosynthetic system. The quality of this process directly determines the subsequent growth trajectory and environmental adaptability of the plant. Hormones, as core components of the plant's signaling molecule network, precisely regulate the entire seedling establishment process through accurate synthesis, metabolism, signal transduction, and interactions, ensuring the temporal sequence and coordination of developmental events. Under different environmental conditions, plants can achieve adaptive development by adjusting key parameters of hormonal regulation mechanisms. This process relies on precise expression of genes related to hormone synthesis and metabolism, efficient operation of signal transduction pathways, transcription factor-mediated regulation, dynamic adjustments of epigenetic modifications, and synergistic gene interactions. Based on this, this study provides a comprehensive analysis of hormonal regulation mechanisms during seedling establishment. It not only reveals the molecular regulatory patterns of early plant development and enhances the theoretical framework of plant developmental biology but also offers crucial theoretical support for breeding plant varieties with strong seedling vigor and excellent stress resistance.*

***Keywords:*** *seedling establishment; hormone regulation; mechanism*

## 1. Introduction

Seedling establishment marks the transition of plants from an heterotrophic stage dependent on stored nutrients in seeds to an autotrophic stage achieving energy self-sufficiency through photosynthesis. This critical process enables plants to respond to environmental challenges and ensure population sustainability. The establishment involves multiple interconnected developmental events, each requiring precise regulatory mechanisms for orderly progression. In natural ecosystems, plant seedlings frequently encounter complex environmental stresses such as light fluctuations, temperature extremes, water scarcity, and nutrient deficiencies. Hormones, as ubiquitous signaling molecules in plants, integrate internal and external signals through intricate regulatory networks to control various physiological processes during seedling establishment, ensuring successful developmental transitions under variable conditions. This study not only enriches the theoretical framework of plant hormone regulation in development but also provides crucial insights for improving plant stress resistance and seedling survival through molecular design, demonstrating significant theoretical value and practical applications.

## 2. Functional localization of core hormones during seedling establishment

### *2.1 Auxin*

Auxin is the core hormone regulating seedling establishment, with its primary functions focusing on cell elongation, organ polarity establishment, and tissue differentiation. Through the local concentration gradient formed by polar transport, auxin precisely regulates the maintenance and activity balance of the apical meristem in the embryonic root, guiding the downward growth of the embryonic root and promoting the initiation and development of lateral root primordia. During the elongation of the embryonic axis, auxin enhances cell elongation capacity by regulating the expression of cell wall relaxation-related genes, while also participating in the temporal regulation of cotyledon outgrowth to

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ensure timely expansion of cotyledons for initiating photosynthesis [1].

### *2.2 Cytokinin*

Cytokinin plays a pivotal role in seedling establishment by regulating cell division, maintaining meristem activity, and coordinating nutrient uptake and distribution. It promotes the proliferation of embryonic root and shoot apical meristem cells by activating cell division-related gene expression, thereby ensuring the formation and growth of organ primordia in seedlings. During root development, cytokinin and auxin form a balance of synergy and antagonism, regulating the density and timing of lateral root development while enhancing the root system's ability to absorb mineral nutrients such as nitrogen and phosphorus, providing essential nutrition for seedling growth. In the development of green organs after emergence, cytokinin facilitates chloroplast development and the expression of photosynthesis-related genes, accelerating the establishment of cotyledon photosynthetic systems and propelling seedlings into the autotrophic growth phase.

### *2.3 Gibberellin*

Gibberellin is a key growth-promoting hormone that breaks seed dormancy and drives seedling emergence and growth, with its core functions focused on promoting cell elongation and organ expansion. It alleviates growth inhibition by degrading the DELLA protein, activates the expression of cell elongation-related genes, and significantly promotes the elongation of the embryonic axis and germinal sheath, providing dynamic support for the embryo root to penetrate the seed coat and the seedling to emerge from the soil layer. In the later stages of seed germination, gibberellin regulates the synthesis of enzymes related to endosperm cell wall degradation, accelerating the decomposition and utilization of endosperm nutrients, thereby supplying energy and materials for early seedling growth [2]. After emergence, gibberellin continues to participate in the regulation of cotyledon expansion, promoting the elongation of cotyledon cells and the maturation of photosynthetic apparatus, while synergizing with auxin to regulate stem elongation, helping seedlings rapidly establish a growth posture adapted to the light environment.

### *2.4 Abscisic acid*

Abscisic acid (ABA) serves dual functions as a negative regulator and stress safeguard during seedling establishment, acting as a critical regulator for balancing growth and survival. By inhibiting the signaling pathways of gibberellins and auxins, ABA delays the elongation of the embryonic axis and the germination process of seeds, ensuring that seedlings remain dormant under unfavorable environmental conditions and thereby enhancing survival probability. When seedlings encounter adverse stress, ABA rapidly accumulates, activating the expression of stress-related genes to regulate stomatal closure, enhance cell membrane stability, and promote the synthesis of osmotic regulatory substances, thereby improving the seedlings' tolerance to stress.

### *2.5 Ethylene*

Ethylene plays a pivotal role in seedling establishment by regulating growth posture and mediating stress adaptation responses, enabling environmental adaptation through modulation of cell growth rates and directions. During germination, ethylene inhibits longitudinal elongation of the embryonic axis while promoting lateral thickening, resulting in a compact growth posture that enhances resistance to soil mechanical resistance. In the regulation of gravitropism and phototropism, ethylene interferes with auxin polar transport, altering its distribution gradient within organs to adjust the growth orientation of the embryonic axis and roots, ensuring precise environmental signal perception and posture adjustment. When encountering stresses such as hypoxia, salinity, or mechanical damage, ethylene rapidly synthesizes and initiates adaptive regulatory programs by modulating the expression of stress response genes, thereby improving seedling stress resistance [3].

## 3. Interaction Network of Hormones during Seedling Establishment

### *3.1 Interaction Mechanism between Auxins and Cytokines*

The dynamic interaction between auxin and cytokinin constitutes the core molecular network

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regulating seedling establishment. Through "concentration gradient equilibrium—cross-talk of signaling pathways," these two hormones collaboratively control embryonic root germination, apical meristem formation, and cotyledon expansion. Auxin establishes concentration gradients between root tips and shoot apices via PIN protein-mediated polar transport, inducing cell elongation and differentiation to lay the foundation for morphogenesis. Cytokinin primarily acts on meristematic regions, activating the ARR family response factors to promote cell division and maintain meristem activity. Their interaction exhibits concentration-dependent antagonism and synergy: low cytokinin concentrations enhance auxin's polar transport efficiency, facilitating embryonic root breakthrough through the seed coat; high concentrations suppress PIN protein expression, thereby inhibiting auxin accumulation and preventing excessive root elongation.

### *3.2 Antagonistic Regulatory Network of Gibberellin and ABA*

Gibberellin and abscisic acid constitute the most critical antagonistic regulatory network during seedling establishment, modulating the balance between seed dormancy termination and seedling stress adaptation through "mutually exclusive activation of signaling pathways—competition for common target genes." Gibberellin alleviates growth inhibition by degrading the DELLA protein, activating downstream gene expression related to cell elongation and starch degradation, promoting embryonic axis elongation and cotyledon expansion, and facilitating rapid morphogenesis after seed coat breakthrough. In contrast, abscisic acid inhibits cell division and elongation by activating transcription factors such as ABI5, maintaining seedling dormancy while enhancing tolerance to early-stage germination stresses like drought and low temperature. This antagonistic relationship persists throughout the entire seedling establishment process: during germination, gibberellin reduces abscisic acid concentration by suppressing the expression of the abscisic acid biosynthesis gene NCED, thereby breaking dormancy; under stress conditions, abscisic acid accelerates gibberellin degradation by upregulating the GA2ox gene expression, suppressing growth to ensure survival.

### *3.3 Synergistic and Antagonistic Effects of Ethylene and Auxin in Root Development*

Ethylene and auxin form a complex interaction relationship of "synergistic regulation of differentiation—antagonistic regulation of elongation" during seedling root development, precisely regulating root morphogenesis and gravitropism through signal pathway crosstalk. In the root elongation zone, ethylene increases local auxin accumulation by promoting the expression of the auxin synthesis gene YUC. High concentrations of auxin further inhibit root cell elongation, forming an "ethylene-auxin" mediated negative regulation pathway for root elongation, thereby preventing excessive root growth that consumes nutrients. In the root crown and lateral root primordium regions, the two hormones exhibit synergistic effects. Ethylene activates the expression of auxin polar transport-related genes, enhancing local auxin accumulation in the lateral root primordium, promoting lateral root formation and root hair differentiation, and expanding the root's absorption area.

### *3.4 Interaction between Jasmonic Acid and Other Hormones in Stress Resistance Regulation*

Jasmonic acid serves as a pivotal regulator in stress response establishment during seedling development. It coordinates the balance between growth and stress adaptation through multidimensional interactions with hormones such as auxin, gibberellin, and abscisic acid. Under stress conditions including pathogen infection or mechanical injury, jasmonic acid activates core transcription factors like MYC2. This dual mechanism enhances seedling defense capabilities by: 1) upregulating stress-responsive genes; and 2) modulating growth rhythms through hormone interactions. Specifically, it synergizes with abscisic acid to increase stress tolerance by upregulating its biosynthesis genes, thereby collectively suppressing growth. Simultaneously, it antagonizes gibberellin by stabilizing DELLA proteins, blocking the gibberellin-mediated growth-promoting pathway. This ensures seedlings prioritize nutrient allocation for stress resistance.

## 4. Adaptive Changes in Hormonal Regulation Mechanisms under Different Environmental Conditions

### *4.1 Effects of Light Conditions on Hormone-Regulated Seedling Establishment*

Light serves as a critical environmental signal during seedling establishment, reshaping hormonal

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regulation mechanisms to adapt to light environment changes by modulating hormone synthesis, transport, and signaling. Variations in light intensity and quality directly influence the efficiency and distribution pattern of auxin polar transport, regulating phototropism in seedlings to ensure precise organ orientation toward light sources. Simultaneously, light inhibits gibberellin synthesis and promotes abscisic acid degradation, preventing excessive growth in dark or low-light conditions and maintaining rational growth configuration. Under strong light conditions, plants increase ethylene synthesis to regulate stomatal opening/closing and protect photosynthetic apparatus, thereby reducing light-induced damage to seedlings.

### *4.2 Adaptive Regulation of Hormonal Control under Temperature Variation*

Temperature variations drive adaptive adjustments in hormonal regulation mechanisms by modulating the activity of hormone-synthesizing enzymes and signaling pathway efficiency, ensuring normal seedling development under different temperature conditions. Under low-temperature conditions, plants significantly increase abscisic acid synthesis while inhibiting gibberellin and auxin production, thereby delaying seed germination and shoot elongation. Simultaneously, they activate frost-resistant gene expression to enhance seedling frost tolerance. In optimal temperature environments, the synthesis efficiency of gibberellin and auxin increases, synergistically promoting cell elongation and organ growth to accelerate seedling establishment. Under high-temperature conditions, ethylene synthesis markedly intensifies, suppressing vertical growth while promoting lateral thickening to form heat-tolerant growth patterns. This process also regulates heat shock protein gene expression, thereby improving seedling tolerance to high-temperature stress.

### *4.3 Regulatory Mechanisms of Hormones on Seedling Survival under Water Stress*

Under water stress, the core of hormonal regulation shifts to ensuring seedling survival, with multiple hormones working synergistically to balance water absorption and consumption. Abscisic acid, the key hormone in water stress response, rapidly accumulates to regulate stomatal closure, reducing water transpiration while promoting root growth and root hair development, thereby enhancing the root system's capacity to absorb soil moisture. Auxin polar transport is adjusted under water stress, guiding roots toward water-rich areas to improve water acquisition efficiency. Ethylene is initially synthesized in moderation during early water stress, suppressing above-ground growth to reduce water consumption. However, as stress intensifies, excessive ethylene inhibits root growth, and at this stage, abscisic acid counteracts this inhibition by suppressing ethylene synthesis.

### *4.4 Hormone-Mediated Seedling Adaptation Strategies under Nutrient Deficiency Conditions*

Under nutrient-deficient conditions, hormones regulate seedling root remodeling and nutrient absorption mechanisms to enable adaptive growth. In nitrogen and phosphorus deficiency, cytokinin synthesis is significantly reduced, leading to slowed aboveground growth. Simultaneously, enhanced polar transport of auxin promotes lateral root and root hair development, increasing root surface area and improving nutrient uptake capacity. Auxin also activates nutrient transport protein gene expression in roots, boosting the efficiency of limited soil nutrient absorption. Abscisic acid accumulates moderately under nutrient stress, inhibiting excessive aboveground growth and optimizing the nutrient distribution ratio between aboveground and underground parts, ensuring adequate nutrient supply for root development.

## 5. Hormonal Regulation Mechanisms during Seedling Establishment

### *5.1 Expression Regulation of Genes Related to Hormone Synthesis and Metabolism*

The precise expression of genes related to hormone synthesis and metabolism serves as the fundamental basis for regulating the dynamic balance of hormone levels during seedling establishment. These genes exhibit distinct tissue-specificity and temporal regulation, displaying differential expression patterns across different developmental stages and tissue locations of seedlings. This ensures the formation of accurate concentration gradients of various hormones at appropriate temporal and spatial points. Gene expression regulation is primarily achieved through transcriptional level modulation, where core regulatory elements bind to transcription factors to activate or inhibit transcription initiation, thereby adjusting the activity of enzymes involved in hormone synthesis and

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metabolism. Simultaneously, hormones themselves regulate the expression of these genes via feedback mechanisms, forming a closed-loop regulatory network to maintain hormonal homeostasis. Imbalances in the expression of these genes can directly lead to hormonal dysregulation, subsequently affecting various physiological processes during seedling establishment and resulting in developmental abnormalities [4].

### *5.2 Functions of Key Genes in Hormone Signal Transduction Pathways*

Key genes in hormone signaling pathways mediate the perception, transmission, and amplification of signals to ensure precise regulation of downstream target gene expression, thereby controlling the establishment of seedling development. These genes encompass multiple categories, including hormone receptor genes, signaling protein genes, and downstream regulatory genes, forming a hierarchically organized signaling network. Hormone receptor genes encode specific receptors that accurately recognize corresponding hormone molecules, triggering conformational changes in the receptor and initiating downstream signaling processes. Signaling protein genes encode proteins such as kinases and phosphatases, which amplify and transmit signals through phosphorylation and dephosphorylation cascade reactions. Downstream regulatory genes are activated upon signal activation, regulating core physiological processes such as cell division, elongation, and differentiation. Key genes in different hormone signaling pathways exhibit cross-interactions, integrating and synergizing signals through shared regulatory nodes to ensure coordinated and unified hormonal regulatory effects. Functional loss of key genes can disrupt signaling pathways, rendering seedlings incapable of perceiving hormone signals, leading to developmental arrest or abnormalities.

### *5.3 Core Mediating Role of Transcription Factors in Hormone Regulation*

Transcription factors serve as key mediators in hormone-regulated seedling establishment. By binding to specific cis-acting elements in target gene promoter regions, they modulate gene expression, thereby translating hormonal signals into developmental control. Different hormone signaling pathways activate distinct transcription factor families that precisely recognize and bind to regulatory regions of downstream developmental genes, initiating or suppressing gene expression. The mediation by transcription factors exhibits remarkable specificity, with varying gene sets regulated by different factors, thus controlling distinct developmental processes. Furthermore, transcription factors interact through complex networks, forming transcriptional regulatory systems that integrate and coordinate diverse hormonal signals. Functional abnormalities in transcription factors can disrupt downstream gene expression, compromising the precision of hormonal regulation and impairing normal seedling development.

### *5.4 Effects of Epigenetic Regulation on Hormone Signaling*

Epigenetic regulation dynamically adjusts the expression of hormone-related genes through mechanisms such as DNA methylation, histone modifications, and non-coding RNA (ncRNA) regulation, thereby enhancing the flexibility and adaptability of hormonal control mechanisms. DNA methylation suppresses gene expression by modifying the promoter regions of hormone synthesis and signal transduction-related genes, thereby regulating hormone levels and signaling efficiency. Histone modifications alter chromatin structure through acetylation and methylation, influencing gene transcriptional accessibility and activating or repressing the expression of hormone-related genes. Non-coding RNAs achieve precise gene expression regulation by targeting the mRNA of hormone-related genes, either by modulating translation processes or promoting mRNA degradation. Epigenetic regulation is reversible and environmentally responsive, enabling dynamic adjustment of hormone-related gene expression patterns in response to environmental changes, allowing seedlings to rapidly adapt to external environmental variations [5].

### *5.5 Co-expression Network of Genes Related to Hormone Regulation*

Hormone-regulated genes establish systematic control over seedling establishment through co-expression networks, ensuring coordinated progression of developmental events. These networks consist of genes involved in hormone synthesis, metabolism, signal transduction, and downstream developmental regulation, forming complex network architectures through direct interactions or indirect regulatory relationships. Core genes serve as regulatory hubs, orchestrating key developmental processes by modulating the expression of multiple downstream genes, while peripheral genes

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participate in network regulation under specific conditions to enhance stability and adaptability. The co-expression network exhibits dynamic characteristics, with the interaction intensity between core regulatory nodes and genes dynamically adjusted during different stages of seedling establishment to meet developmental requirements. Environmental signals can reshape network architecture by regulating the expression of key genes, enabling rapid environmental response through hormonal mechanisms. Network integrity and stability directly determine the precision and efficiency of hormonal regulation, while structural disruptions may lead to developmental disorders in seedlings.

## 6. Conclusion

The hormonal regulation mechanism during seedling establishment constitutes a complex system comprising core hormone functional localization, environmental adaptability adjustment, and precise molecular-level regulation. These hierarchical regulatory mechanisms interweave and synergize to ensure the successful transition of seedlings from heterotrophy to autotrophy. Although significant progress has been made in studying hormonal regulation mechanisms, fundamental molecular mechanisms underlying the coupling of environmental and hormonal signals, as well as the dynamic regulatory patterns of gene synergistic networks, still require further exploration. Future research integrating multi-omics technologies and gene editing techniques will enable precise identification of core components and their interactions within hormonal regulatory networks. This advancement will further refine the theoretical framework of plant early development, provide critical theoretical support for breeding plant varieties with enhanced stress resistance and superior seedling vigor, and contribute to ecosystem restoration and sustainable agricultural development.

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