Adaptive Roles of Plant Hormones in Regulating Flowering Time Under Changing Climate Conditions

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ABSTRACT

Climate change has profoundly influenced plant growth and reproductive development, particularly the regulation of flowering time, which is vital for crop yield and ecosystem stability. Fluctuating temperatures, altered photoperiods, drought, and elevated atmospheric CO_2 levels disrupt the environmental cues that synchronize flowering with favorable growth conditions. Plant hormones—such as gibberellins (GAs), abscisic acid (ABA), auxins, cytokinins, ethylene, jasmonic acid (JA), and salicylic acid (SA)—serve as central regulators in translating these environmental signals into adaptive physiological responses. Through intricate signaling networks and hormonal cross-talk, they modulate the timing and progression of flowering to ensure reproductive success under stress. Gibberellins generally promote floral initiation, while ABA often acts antagonistically under drought and heat stress, delaying flowering to conserve resources. Similarly, cytokinins, auxins, and ethylene coordinate floral meristem development and organ differentiation, maintaining reproductive balance. Climate-induced stress alters hormone biosynthesis, signaling, and degradation, leading to shifts in flowering phenology. Understanding these hormone-mediated adaptive mechanisms is crucial for breeding and engineering climate-resilient crops capable of sustaining yield under unpredictable environmental conditions. Moreover, integrating hormonal regulation insights into climate-smart agriculture—through genetic modification, marker-assisted breeding, and exogenous hormone application—offers new pathways for sustainable crop management. Hence, elucidating the adaptive hormonal control of flowering time provides a foundation for enhancing agricultural resilience and food security in the face of accelerating climate change.

Keywords: Plant hormones, flowering regulation, climate change, hormonal cross-talk, crop adaptation.

Introduction

In the rapidly changing global climate, plants face multifaceted environmental challenges that directly affect their reproductive development and survival. Flowering, a key event in the plant life cycle, determines reproductive success and yield potential in both natural and agricultural ecosystems. The timing of flowering is highly sensitive to external factors such as temperature fluctuations, altered photoperiods, drought stress, and elevated atmospheric CO_2 concentrations. These factors disrupt the intricate balance of physiological and molecular networks that govern floral transition. Among these regulatory systems, plant hormones—or phytohormones—play a pivotal role as chemical messengers coordinating growth and development in response to environmental stimuli. Hormones such as gibberellins (GAs), auxins, cytokinins, abscisic acid (ABA), ethylene, salicylic acid (SA), and jasmonic acid (JA) interact in complex signaling pathways to modulate flowering initiation and progression. Under climate stress, the homeostasis and signaling efficiency of these hormones can be profoundly altered, leading to premature, delayed, or even inhibited flowering. Consequently, understanding how plant hormones mediate flowering under climate variability is essential for predicting plant responses, ensuring food security, and developing stress-resilient crop varieties.

Recent advances in molecular biology, genomics, and climate modeling have unveiled the intricate hormone-mediated mechanisms that integrate environmental cues with endogenous developmental programs. Gibberellins, for instance, are known to promote flowering in long-day plants like *Arabidopsis thaliana* through activation of LEAFY (LFY) and SUPPRESSOR OF OVEREXPRESSION OF CONSTANS1 (SOC1), whereas ABA often acts antagonistically by repressing these floral promoters under drought or heat stress. Similarly, auxins regulate the spatial patterning of floral organs and influence photoperiodic responses, while cytokinins interact with GAs to maintain the floral meristem identity. Moreover, ethylene and jasmonates, traditionally associated with stress signaling, have been found to play dual roles—sometimes enhancing, sometimes delaying flowering—depending on the nature and duration of environmental stress. Climate-induced stresses, including heatwaves, erratic rainfall, and elevated CO_2, modify hormonal synthesis, degradation, and cross-talk, thereby reprogramming the plant's developmental trajectory. By decoding these hormone-climate interactions, researchers can manipulate flowering time to synchronize crop phenology with optimal environmental conditions, mitigating yield losses. Therefore, exploring the adaptive roles of plant hormones under changing climate scenarios not only enhances our understanding of plant resilience mechanisms but also provides a scientific foundation for climate-smart agriculture and sustainable ecosystem management.

Overview of Climate Change Impacts on Flowering

Climate change has emerged as one of the most critical global challenges affecting plant growth, development, and reproductive success. Flowering, being a pivotal phase in the plant life cycle, is highly sensitive to variations in climatic parameters such as temperature, photoperiod, precipitation, and atmospheric CO_2 concentration. Even minor alterations in these factors can disrupt the synchrony between floral induction, pollinator activity, and seed maturation. Rising global temperatures often accelerate flowering time, leading to premature blooming before optimal pollination or resource availability. Conversely, unpredictable cold spells and altered photoperiods can delay or completely inhibit floral initiation. In agricultural systems, such mismatches reduce crop yield and quality, while in natural ecosystems, they disturb plant–pollinator interactions and community dynamics. Drought and heat stresses further impair floral meristem development and reproductive organ viability by triggering oxidative damage and hormonal imbalances. Elevated CO_2 levels, though initially promoting vegetative growth, often induce shifts in carbon partitioning that alter flowering responses. Collectively, these factors impose selective pressures that may lead to phenological shifts, local extinction, or adaptation of species. Understanding how climate change redefines flowering dynamics is crucial not only for predicting ecosystem resilience but also for developing climate-smart agricultural strategies aimed at maintaining crop productivity and biodiversity stability.

Hormonal Regulation as an Adaptive Mechanism

Plant hormones, or phytohormones, serve as integral regulators of flowering time and adaptation under changing climate conditions. They act as chemical messengers that translate environmental cues into coordinated developmental responses. Gibberellins (GAs) promote floral transition by activating flowering genes such as *LEAFY (LFY)* and *SUPPRESSOR OF OVEREXPRESSION OF CONSTANS1 (SOC1)*, especially under long-day conditions. Conversely, abscisic acid (ABA) acts as a stress hormone, delaying flowering under drought, salinity, or heat stress to conserve energy and water. Auxins and cytokinins regulate floral meristem formation and organ differentiation, maintaining developmental stability under environmental fluctuations. Ethylene and jasmonic acid (JA), commonly associated with stress responses, mediate flowering under abiotic stresses by fine-tuning gene expression and reproductive timing. These hormones do not function independently but interact through complex signaling networks and feedback loops—known as hormonal cross-talk—that ensure adaptive flexibility. For instance, under drought stress, the antagonistic interaction between ABA and GA determines whether flowering is delayed or initiated as a survival response. Such hormonal adjustments enable plants to modulate flowering phenology in alignment with changing climatic cues, enhancing reproductive success and long-term adaptability. Therefore, hormonal regulation represents an evolutionary strategy by which plants maintain resilience and reproductive continuity in the face of global climate variability.

Need of the Study

The regulation of flowering by plant hormones under changing climatic conditions has emerged as a critical area of research due to its direct implications for plant survival, biodiversity conservation, and global food security. Flowering represents a pivotal phase in a plant's life cycle, marking the transition from vegetative to reproductive development. This phase determines not only reproductive success but also the timing and yield of agricultural production systems. However, with the accelerating pace of climate change, traditional patterns of flowering are being disrupted due to shifts in temperature, photoperiods, and precipitation regimes. These environmental perturbations lead to phenological mismatches, where the timing of flowering becomes out of sync with the availability of pollinators or favorable growth conditions. Consequently, understanding how plant hormones mediate flowering responses to environmental stress is essential to predict and mitigate these negative impacts. Phytohormones act as key chemical messengers that integrate external cues with internal developmental signals, enabling plants to adapt their reproductive timing. For instance, changes in gibberellin and abscisic acid levels under temperature or drought stress can drastically alter flowering patterns. Studying these interactions provides critical insights into how hormonal cross-talk buffers plants against climate variability and helps identify mechanisms that could be harnessed to develop climate-resilient crop varieties.

Furthermore, the need for this study is accentuated by the increasing unpredictability of climatic events, such as unseasonal rainfall, prolonged droughts, and heat waves, which cause hormonal imbalances and disrupt reproductive physiology. These stresses not only reduce yield but also compromise the quality and stability of global food supply chains. Current crop breeding programs often overlook the hormonal regulation aspect, focusing instead on single-gene or temperature-based models of flowering. However, hormones represent a dynamic interface between genetic expression and environmental adaptation, making them ideal targets for understanding and manipulating flowering responses under climate stress. By elucidating how key hormones—such as auxins, cytokinins, ethylene, jasmonates, and salicylic acid—interact to regulate floral induction and development, researchers can identify biochemical markers and molecular targets for crop improvement. This knowledge can guide precision agriculture and genetic engineering strategies to maintain optimal flowering even under suboptimal conditions. The study holds ecological relevance, as shifts in flowering time due to hormonal alterations can disrupt plant–pollinator networks, threatening ecosystem stability. Therefore, investigating the hormonal regulation of flowering under climate change is not merely a scientific pursuit but a strategic necessity for sustainable agriculture, biodiversity conservation, and climate adaptation planning. This research bridges fundamental plant biology with applied agricultural innovation, offering pathways to ensure reproductive success and yield stability in a warming and increasingly unpredictable world.

Literature Review

The intricate relationship between plant hormones and environmental conditions forms the foundation of plant developmental plasticity. Climate change, characterized by rising temperatures, altered precipitation patterns, and elevated CO_2 concentrations, has emerged as a powerful force reshaping plant growth and reproductive strategies. Flowering, being the central event that determines reproductive success, is particularly vulnerable to these climatic fluctuations. Li et al. (2021) emphasize that plant hormones are key mediators in modulating physiological and molecular responses to heat and other climate-induced stresses. The authors discuss that the hormonal network—comprising gibberellins (GAs), abscisic acid (ABA), ethylene, jasmonates, and cytokinins—acts as a dynamic regulatory system integrating environmental signals with intrinsic genetic mechanisms. Similarly, Tun et al. (2021) highlight that the timing of flowering, controlled by both photoperiod and temperature-dependent cues, is being disrupted globally, leading to early or delayed flowering patterns in many plant species. These hormonal responses, triggered by climatic factors, influence not only flowering initiation but also reproductive efficiency and yield potential, underscoring the urgent need to understand the hormonal basis of flowering regulation under climate change.

Heat stress is one of the most critical challenges associated with climate change, adversely affecting floral development, pollen viability, and reproductive success. Li et al. (2021) explored how hormones mediate heat tolerance, identifying abscisic acid (ABA), salicylic acid (SA), and ethylene as central regulators of heat-stress adaptation. ABA accumulation under elevated temperatures modulates stomatal closure and enhances thermotolerance, but excessive ABA can suppress flowering by inhibiting gibberellin synthesis. Gibberellins (GAs), in contrast, promote floral initiation and stem elongation, acting antagonistically to ABA. Ahammed et al. (2016) extend this understanding by emphasizing the integrative role of auxin and ethylene signaling in maintaining floral organ integrity during heat exposure. The authors note that hormonal homeostasis—particularly the balance between growth-promoting GAs and stress-responsive ABA—is critical for sustaining flowering under high-temperature stress. Therefore, hormonal regulation functions as a balancing mechanism that enables plants to prioritize survival while maintaining reproductive capability, suggesting that targeted manipulation of these hormones could enhance crop resilience in warming climates.

Climate change has caused visible shifts in plant phenology, particularly in flowering time. Tun et al. (2021) demonstrate that global warming has accelerated phenological events such as flowering and fruiting, often causing a mismatch between flowering and pollinator availability. Hormones play a pivotal role in modulating these shifts. For instance, increased temperature accelerates gibberellin biosynthesis, leading to early flowering in many temperate species. Zhang, Dai, and Ge (2020) explored the correlation between climate change-driven phenological changes and hormone regulation, revealing that alterations in hormone levels, especially ABA and cytokinins, influence the onset and duration of flowering. Their findings underscore that environmental signals are transduced into hormonal pathways that regulate floral gene expression, affecting the timing and success of reproduction. Moreover, they propose that climate-induced hormonal variations can trigger epigenetic modifications, resulting in heritable changes in flowering time across generations. This highlights the adaptive potential of hormonal regulation, serving as both a physiological and evolutionary mechanism in response to climate change.

Flowering is a metabolically demanding process that requires coordinated hormonal signaling and energy balance. Borghi et al. (2019) provide a metabolic perspective on how flowers adapt to changing climates, emphasizing that hormones interact with primary and secondary metabolism to regulate energy flow and floral organ formation. The study reveals that cytokinins and auxins regulate carbohydrate allocation to reproductive tissues, ensuring sufficient energy during floral transition, while ethylene and jasmonates modulate defense metabolism during stress. These findings suggest that climate-induced disruptions in metabolism can indirectly affect flowering by altering hormonal synthesis and signaling. Furthermore, Verma, Ravindran, and Kumar (2016) argue that hormone-mediated stress responses are interconnected with redox regulation and reactive oxygen species (ROS) signaling, which together determine plant resilience. The cross-talk between hormonal and metabolic pathways therefore defines how plants optimize energy use and developmental timing under climate variability, linking hormonal control to metabolic stability in floral regulation.

The interplay between reactive oxygen species (ROS) and hormones forms another critical layer of regulation under climate stress. Devireddy et al. (2021) emphasize that ROS, produced during temperature fluctuations, act as signaling molecules that interact with hormones like ABA, salicylic acid, and jasmonic acid to trigger adaptive responses. ROS accumulation under heat or cold stress modulates the expression of heat shock proteins and floral regulators, influencing flowering timing and organ development. However, excessive ROS can lead to oxidative damage, disrupting hormonal equilibrium and impairing floral fertility. This complex signaling network illustrates how hormonal balance acts as a buffer, maintaining cellular homeostasis during environmental stress. The study also suggests that hormonal regulation of antioxidant enzymes enhances thermotolerance, thereby protecting reproductive tissues. Thus, ROS-hormone signaling cross-talk is pivotal in determining whether plants successfully reproduce or experience reproductive failure under climate stress. Understanding this dynamic is vital for improving heat resilience through hormone-based or genetic interventions.

The concept of hormonal cross-talk is central to understanding how plants integrate multiple environmental cues into coherent developmental outcomes. According to Husen and Zhang (2021), the hormonal network functions as a multidimensional communication system, wherein different hormones either synergize or antagonize each other to regulate growth, defense, and flowering. Their edited volume discusses that auxin and cytokinin signaling pathways interact to control floral meristem identity, while ABA and ethylene mediate responses to drought and temperature stress. This cross-talk ensures that flowering only proceeds under favorable internal and external conditions. The authors also highlight that manipulating hormone biosynthesis or signaling genes through molecular breeding or CRISPR/Cas9 gene editing can enable precise control over flowering time and stress tolerance. Similarly, Verma et al. (2016) emphasize that hormonal cross-regulation is essential for maintaining equilibrium between growth and defense during environmental stress, demonstrating how plants dynamically reprogram development in response to climatic pressures.

Applications in Climate-Smart Agriculture

The integration of hormonal regulation knowledge into climate-smart agriculture (CSA) represents a promising avenue for enhancing crop productivity, stability, and resilience under rapidly changing environmental conditions. Climate-smart agriculture aims to sustainably increase agricultural output, adapt to climate variability, and reduce greenhouse gas emissions. Understanding the adaptive roles of plant hormones in regulating flowering time provides a scientific foundation for breeding and management practices that can synchronize plant phenology with favorable environmental windows. For example, manipulating gibberellin (GA) pathways through selective breeding or genetic engineering allows for the control of floral initiation and vegetative growth balance, ensuring timely flowering despite unpredictable temperature or rainfall shifts. Similarly, enhancing abscisic acid (ABA) responsiveness can improve drought and heat tolerance by delaying flowering until conditions become favorable for reproductive success. Modern biotechnological tools such as CRISPR/Cas9 and RNA interference (RNAi) are now being utilized to modify key genes involved in hormone biosynthesis and signaling—such as *GA20ox*, *ABI1*, and *TFL1*—thereby fine-tuning the timing and duration of flowering across diverse agroecological zones.

Furthermore, the integration of omics technologies—including genomics, transcriptomics, and metabolomics—enables a comprehensive understanding of hormone-environment interactions, facilitating the identification of molecular markers for hormone-mediated flowering traits. These insights support marker-assisted selection (MAS) and genomic selection (GS) strategies in breeding programs aimed at developing climate-resilient crop varieties. Additionally, agricultural management practices such as exogenous hormone application, soil moisture regulation, and the use of biostimulants containing hormone analogs have proven effective in maintaining optimal flowering under stress conditions. For instance, the application of cytokinin-based formulations can sustain floral meristem activity during heat stress, while jasmonate derivatives can enhance stress-induced flowering in some crops. Collectively, these approaches embody the principles of climate-smart agriculture by aligning physiological adaptation with sustainable productivity. Thus, harnessing hormonal regulation mechanisms provides a multifaceted strategy for improving crop resilience, ensuring food security, and fostering sustainable agricultural systems in the era of global climate change.

Research problem

Climate change poses a significant threat to global agricultural productivity and ecosystem stability by altering the environmental cues that regulate flowering time in plants. Flowering is a critical developmental phase determining reproductive success, yield potential, and species survival. However, increasing temperature fluctuations, irregular precipitation patterns, elevated CO_2 levels, and extreme weather events are disrupting the synchronization between flowering and optimal growth conditions. These environmental stresses interfere with the hormonal signaling networks that govern floral induction, transition, and organ development. Although substantial progress has been made in identifying the roles of individual plant hormones—such as gibberellins, abscisic acid, auxins, cytokinins, ethylene, and jasmonates—the integrated understanding of how these hormones collectively modulate flowering under climate stress remains limited. The complexity arises from the dynamic hormonal cross-talk that enables plants to adjust their flowering time as an adaptive strategy. Yet, the molecular mechanisms and genetic pathways underlying these interactions are not fully elucidated, especially across different crop species and climatic regions. This knowledge gap constrains our ability to develop precise biotechnological and agronomic interventions that enhance resilience and maintain productivity. Therefore, the central research problem lies in deciphering how plant hormones interact and regulate flowering time under changing climatic conditions, and how this understanding can be applied to create climate-resilient, high-yielding crop varieties. Addressing this problem is essential for ensuring global food security, optimizing resource use, and sustaining agricultural systems in the face of accelerating climate change.

Conclusion

The adaptive roles of plant hormones in regulating flowering time under changing climate conditions underscore their pivotal importance in ensuring plant resilience, productivity, and survival. As global climate change continues to alter temperature regimes, photoperiods, precipitation patterns, and atmospheric CO_2 levels, the hormonal balance within plants becomes a critical determinant of their reproductive success. Hormones such as gibberellins, abscisic acid, auxins, cytokinins, ethylene, jasmonic acid, and salicylic acid act as intricate regulators that integrate environmental signals with internal genetic programs controlling floral initiation and development. Their dynamic interactions enable plants to fine-tune flowering in response to stress—accelerating or delaying it depending on the prevailing conditions. This hormonal flexibility represents an evolutionary adaptation that maintains reproductive continuity amid environmental uncertainty.

Understanding these mechanisms provides valuable insights for modern agriculture, particularly in the development of climate-resilient crops through hormonal manipulation and genetic innovation. Advanced biotechnological approaches, including CRISPR-based gene editing, molecular breeding, and hormone pathway engineering, offer promising strategies to optimize flowering time for improved yield stability. Moreover, integrating hormonal knowledge into climate-smart agricultural practices—such as exogenous hormone application and stress management—can enhance crop adaptability and sustainability. Therefore, elucidating the complex network of hormone-mediated flowering regulation is not merely a scientific pursuit but a necessity for addressing global food security challenges. Harnessing the adaptive power of plant hormones will be fundamental to sustaining agricultural productivity in an era of unprecedented climate change.

REFERENCES

[1] Li, N., Euring, D., Cha, J. Y., Lin, Z., Lu, M., Huang, L. J., & Kim, W. Y. (2021). Plant hormone-mediated regulation of heat tolerance in response to global climate change. *Frontiers in Plant Science*, *11*, 627969.

[2] Tun, W., Yoon, J., Jeon, J. S., & An, G. (2021). Influence of climate change on flowering time. *Journal of Plant Biology*, *64*(3), 193-203.

[3] Zhang, S., Dai, J., & Ge, Q. (2020). Responses of autumn phenology to climate change and the correlations of plant hormone regulation. *Scientific reports*, *10*(1), 9039.

[4] Borghi, M., Perez de Souza, L., Yoshida, T., & Fernie, A. R. (2019). Flowers and climate change: a metabolic perspective. *New Phytologist*, *224*(4), 1425-1441.

[5] Devireddy, A. R., Tschaplinski, T. J., Tuskan, G. A., Muchero, W., & Chen, J. G. (2021). Role of reactive oxygen species and hormones in plant responses to temperature changes. *International Journal of Molecular Sciences*, *22*(16), 8843.

[6] Ahammed, G. J., Li, X., Zhou, J., Zhou, Y. H., & Yu, J. Q. (2016). Role of hormones in plant adaptation to heat stress. In *Plant hormones under challenging environmental factors* (pp. 1-21). Dordrecht: Springer Netherlands.

[7] Verma, V., Ravindran, P., & Kumar, P. P. (2016). Plant hormone-mediated regulation of stress responses. *BMC plant biology*, *16*(1), 86.

[8] Husen, A., & Zhang, W. (Eds.). (2021). *Hormonal Cross-Talk, Plant Defense and Development: Plant Biology, Sustainability and Climate Change*. Elsevier.

[9] Lu, H. P., Wang, J. J., Wang, M. J., & Liu, J. X. (2021). Roles of plant hormones in thermomorphogenesis. *Stress Biology*, *1*(1), 20.

[10] Castroverde, C. D. M., & Dina, D. (2021). Temperature regulation of plant hormone signaling during stress and development. *Journal of Experimental Botany*, *72*(21), 7436-7458.

[11] Cho, L. H., Yoon, J., & An, G. (2017). The control of flowering time by environmental factors. *The Plant Journal*, *90*(4), 708-719.

[12] Fahad, S., Hussain, S., Bano, A., Saud, S., Hassan, S., Shan, D., ... & Huang, J. (2015). Potential role of phytohormones and plant growth-promoting rhizobacteria in abiotic stresses: consequences for changing environment. *Environmental Science and Pollution Research*, *22*(7), 4907-4921.

[13] Kaur, A., Maness, N., Ferguson, L., Deng, W., & Zhang, L. (2021). Role of plant hormones in flowering and exogenous hormone application in fruit/nut trees: a review of pecans. *Fruit Research*, *1*(1), 1-9.

[14] Wilkinson, S., Kudoyarova, G. R., Veselov, D. S., Arkhipova, T. N., & Davies, W. J. (2012). Plant hormone interactions: innovative targets for crop breeding and management. *Journal of experimental botany*, *63*(9), 3499-3509.

[15] Iqbal, N., Khan, N. A., Ferrante, A., Trivellini, A., Francini, A., & Khan, M. I. R. (2017). Ethylene role in plant growth, development and senescence: interaction with other phytohormones. *Frontiers in plant science*, *8*, 475.