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Climate-Responsive Hormonal Adaptation in Plants: Adaptive Roles of Phytohormones in Regulating Flowering Time Under Changing Environmental Conditions

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ABSTRACT: Climate change has become one of the major environmental factors influencing plant growth, development and reproductive success. Changes in temperature, rainfall patterns, atmospheric carbon dioxide concentration, drought conditions and light availability can significantly affect the timing of flowering in plants. Flowering time is an important developmental process that determines reproductive success, seed production and species survival. Plant hormones, also known as phytohormones, play an essential role in regulating this process by coordinating internal developmental signals with external environmental conditions.

The present review-based research paper examines the adaptive roles of major plant hormones, including gibberellins, abscisic acid, auxins, cytokinins, ethylene, jasmonic acid and salicylic acid, in regulating flowering time under changing climatic conditions. Particular attention is given to hormonal interactions under high-temperature stress, drought, waterlogging, altered photoperiod and other environmental disturbances. The study also discusses the interaction between phytohormones and flowering-related molecular pathways, including FLOWERING LOCUS T (FT), CONSTANS (CO) and FLOWERING LOCUS C (FLC).

The paper proposes an integrated climate-responsive hormonal adaptation framework to explain how plants adjust their reproductive development under environmental stress. Understanding these mechanisms may contribute to climate-resilient crop improvement, sustainable agricultural production and the conservation of plant biodiversity.

1. INTRODUCTION

Flowering is one of the most important stages in the life cycle of flowering plants, as it marks the transition from vegetative growth to reproductive development. The timing of flowering plays a significant role in determining when plants produce flowers, fruits and seeds. Appropriate flowering time enables plants to complete their reproductive cycle under favourable environmental conditions, thereby ensuring successful reproduction and the continuation of plant species. However, global climate change is increasingly altering the environmental conditions required for normal plant growth and development. Rising temperatures, irregular rainfall, prolonged drought, unexpected cold periods and changes in seasonal light conditions are significantly influencing plant reproductive processes. These environmental changes may result in early or delayed flowering, reduced flower production and, in some cases, reproductive failure.

Plants have developed several physiological and molecular mechanisms to respond to changing environmental conditions. Among these mechanisms, plant hormones, also known as phytohormones, play an essential role in regulating growth, development, stress responses and reproductive processes. Gibberellins promote stem elongation and flowering in several plant species, while abscisic acid regulates drought responses and interacts with flowering-related pathways. Auxins contribute to plant development and floral organ formation, whereas cytokinins influence cell division, shoot development and the transition from vegetative to reproductive growth. Similarly, ethylene participates in environmental stress responses and reproductive

development. Jasmonic acid regulates plant defence mechanisms and may influence flowering time, while salicylic acid plays an important role in plant defence and interacts with different flowering regulatory pathways.

Importantly, these plant hormones do not function independently; rather, they interact through complex physiological, biochemical and molecular signalling networks. Their combined activities determine how plants respond and adapt to environmental fluctuations. Recent research has demonstrated that hormonal signalling is closely associated with genetic and epigenetic mechanisms involved in the regulation of floral transition (Li et al., 2024). Similarly, environmental factors such as temperature, photoperiod and water availability influence flowering through interconnected regulatory pathways (Niu et al., 2023). Therefore, understanding the adaptive roles and interactions of plant hormones is essential for explaining how plants regulate flowering time and maintain successful reproductive development under changing climatic conditions. Such knowledge may also contribute to developing climate-resilient crop varieties and improving agricultural productivity in the face of global climate change.

2. NEED AND SIGNIFICANCE OF THE STUDY

Climate change is creating significant challenges for natural vegetation and agricultural crops by altering the environmental conditions necessary for normal plant growth and reproductive development. Traditional flowering patterns are becoming increasingly unpredictable in regions experiencing irregular seasonal changes, rising temperatures, variations in rainfall and prolonged periods of drought. Changes in temperature may accelerate flowering in certain plant species, while excessive heat stress can negatively affect flower formation, pollen viability, fertilisation and overall reproductive success in others. Similarly, water scarcity influences the production and distribution of plant hormones, particularly abscisic acid, and modifies the hormonal balance responsible for regulating vegetative growth and reproductive development. These changes may directly or indirectly affect the timing, duration and success of flowering. In this context, the present study is significant because it explains the relationship between plant hormones and flowering time and examines how hormonal responses are influenced by changing environmental conditions. It also investigates the possible physiological, biochemical and molecular mechanisms through which plants adapt to temperature fluctuations, drought and other climate-related stresses. Furthermore, the study highlights the importance of interactions among different plant hormones in regulating floral initiation and reproductive development under environmental stress conditions. Understanding these mechanisms can provide a scientific foundation for developing climate-resilient crop varieties with improved flowering stability, reproductive efficiency and agricultural productivity. The study also identifies important research opportunities in plant physiology, molecular biology, genetics and agricultural biotechnology, particularly in understanding the role of hormonal signalling networks in maintaining plant reproductive performance under changing climatic conditions.

3. OBJECTIVES OF THE STUDY

The major objectives are:

1. To examine the adaptive roles of different phytohormones in regulating flowering time under changing climatic conditions.

2. To investigate the interaction between environmental stresses and hormonal signalling pathways during floral transition.

3. To propose an integrated hormonal adaptation framework for improving plant reproductive stability and climate resilience.

4. RESEARCH METHODOLOGY

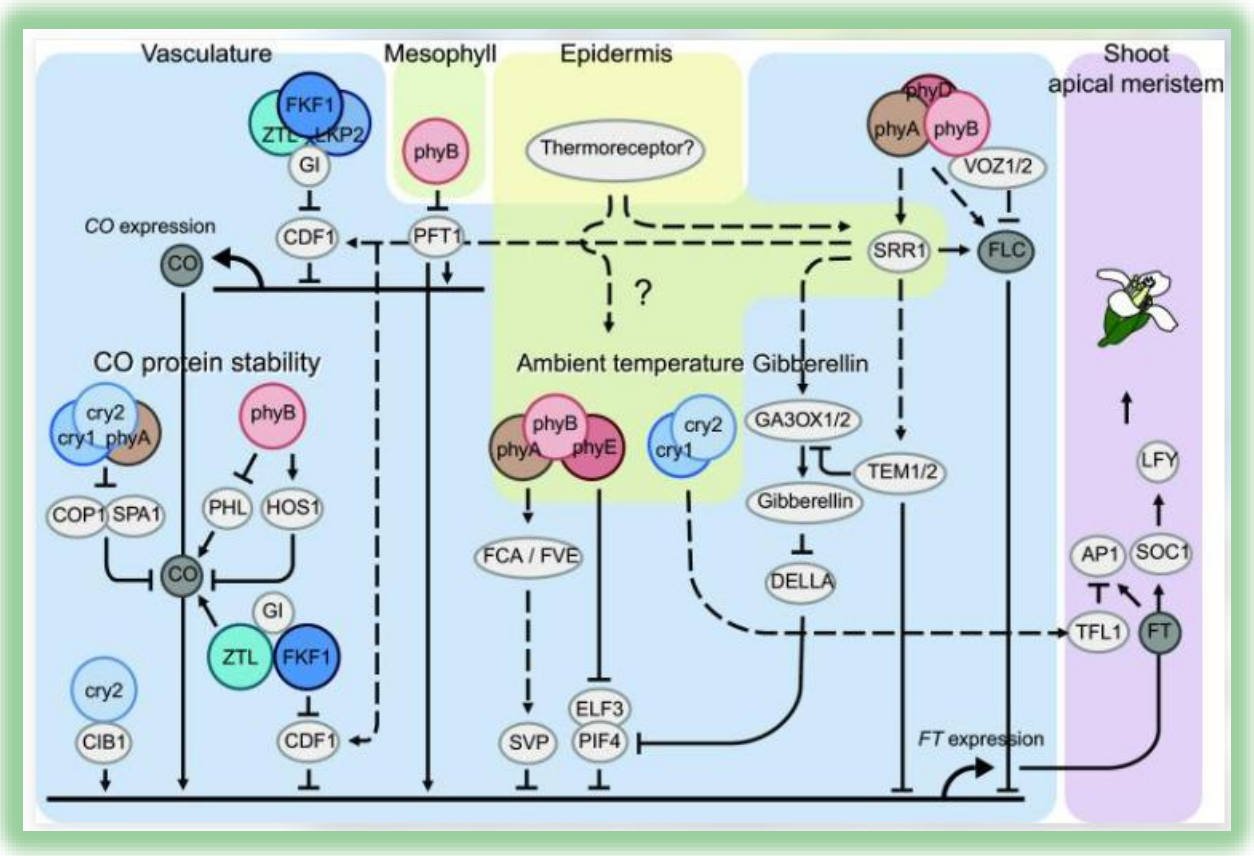
The present study adopts a descriptive and analytical review-based research methodology to examine the adaptive roles of plant hormones in regulating flowering time under changing climatic conditions. The study is primarily based on published scientific literature related to plant physiology, phytohormones, flowering regulation, environmental stress responses and climate adaptation. Relevant information is collected from peer-reviewed research articles, scientific review papers, plant physiology journals, molecular biology publications and research studies focusing on the effects of climate change on plant growth and reproductive development. Particular attention is given to scientific investigations concerning the role of gibberellins in flowering regulation, abscisic acid in drought stress responses, auxin and cytokinin signalling in plant development, ethylene in reproductive processes, and jasmonic acid and salicylic acid in plant defence and stress adaptation. The review also considers the environmental regulation of flowering-related genes and the influence of temperature fluctuations, photoperiod changes and water availability on reproductive development.

Natural Resources for Human Health
eISSN: 2583-1194

The collected scientific information is examined through comparative and thematic analysis to understand the functions of different plant hormones, their interactions and their responses to changing environmental conditions. The major hormonal pathways are compared on the basis of their physiological functions, molecular signalling mechanisms, environmental responses and possible effects on flowering initiation and timing. Particular emphasis is placed on understanding how hormonal interactions contribute to maintaining reproductive development under temperature and water stress. Furthermore, the available scientific evidence is synthesised to develop a conceptual understanding of hormonal adaptation and climate-responsive flowering regulation. Since the present study is a literature-based review, it does not claim to present new laboratory observations, field experiments or experimentally measured results. Instead, it develops an analytical framework based on previously published scientific findings.

5. ROLE OF MAJOR PLANT HORMONES IN FLOWERING REGULATION

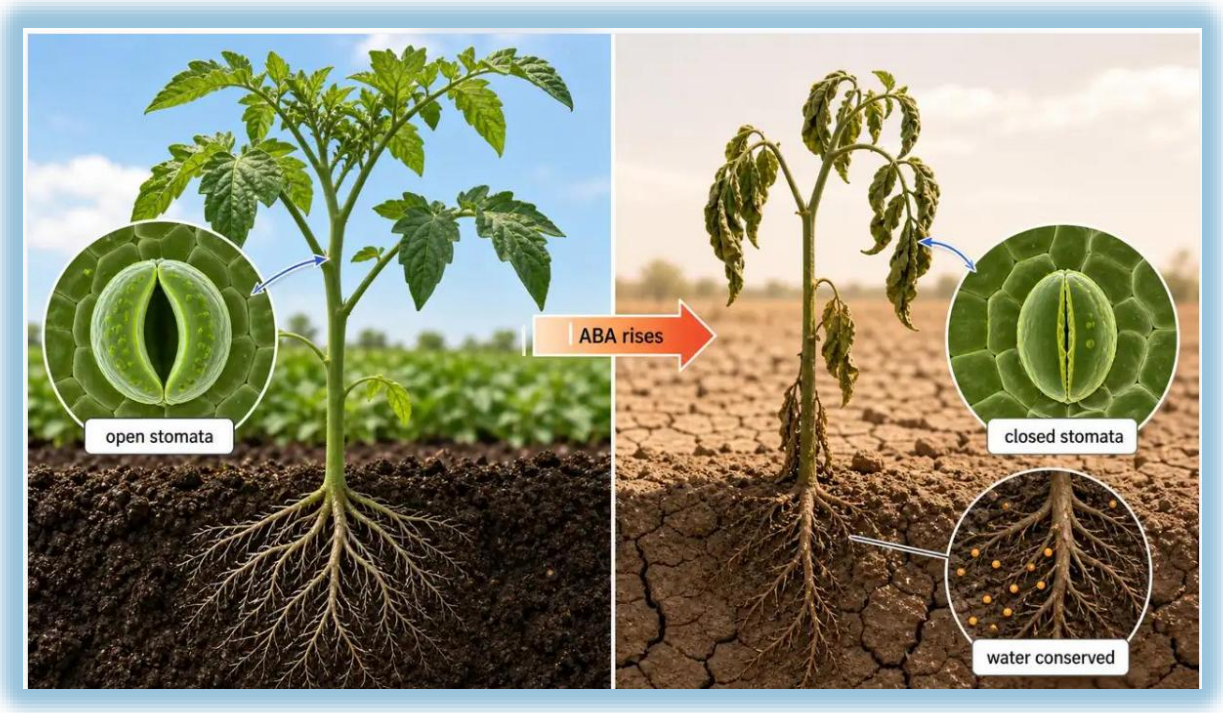
5.1 Gibberellins (GA): Important Regulators of Floral Transition



Gibberellins (GAs) are important plant hormones that regulate several physiological and developmental processes, including seed germination, stem elongation, leaf development and flowering. They play a particularly significant role in controlling the transition from vegetative growth to reproductive development. In many plant species, gibberellins promote flowering by influencing the expression and activity of flowering-related genes. One of the important molecular mechanisms involved in gibberellin signalling is the degradation of DELLA proteins, which function as repressors of gibberellin responses. When active gibberellin binds to its receptor GID1 (Gibberellin Insensitive Dwarf 1), the resulting interaction promotes the recognition and degradation of DELLA proteins through the ubiquitin-proteasome pathway. The removal of these repressors allows different transcriptional regulators to activate gibberellin-responsive developmental processes, including flowering in certain plant species. Thus, the gibberellin signalling pathway plays an important role in regulating the timing of floral transition.

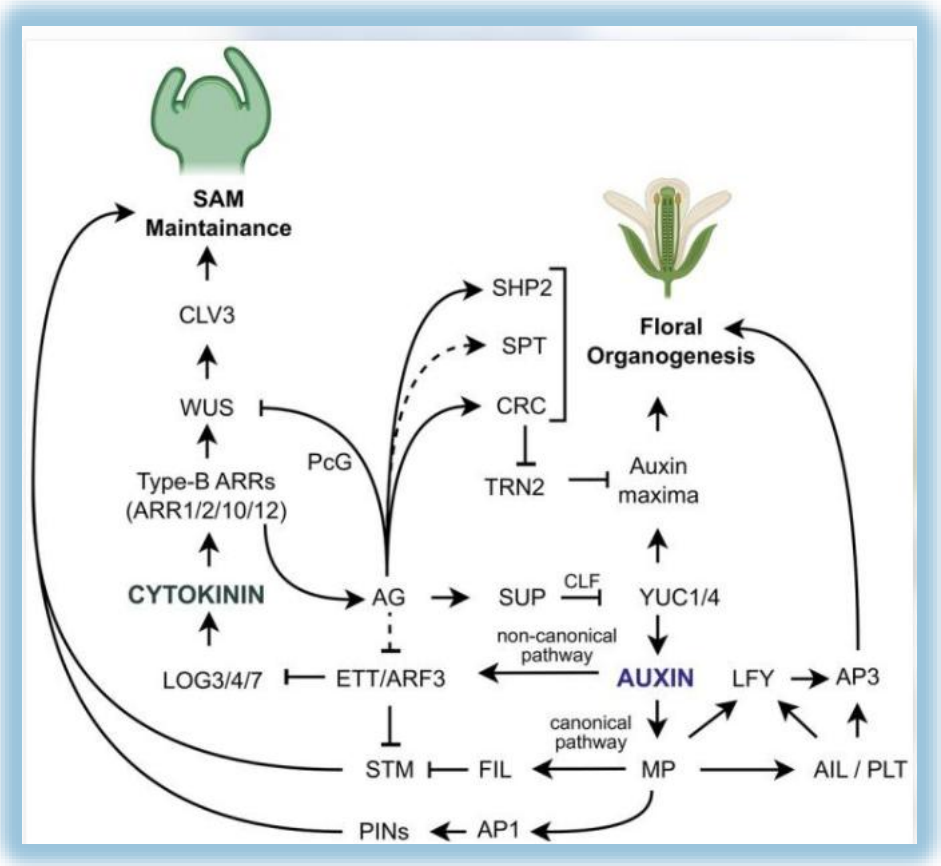
Under changing climatic conditions, gibberellin biosynthesis and signalling may be influenced by variations in temperature and other environmental factors. Increased temperatures can modify gibberellin activity and accelerate flowering in some plant

species, while prolonged heat stress may negatively affect reproductive tissues, pollen development, fertilisation and successful seed formation. The interaction between gibberellin signalling and environmental responses therefore represents an important mechanism connecting temperature conditions with reproductive development. From an adaptive perspective, gibberellins help plants regulate flowering according to favourable environmental conditions, influence the timing of floral transition and contribute to reproductive development under changing climatic conditions. Understanding gibberellin-related molecular pathways may also provide valuable opportunities for crop improvement through the development of varieties with more stable flowering patterns, improved reproductive performance and greater adaptability to climate-related stresses.



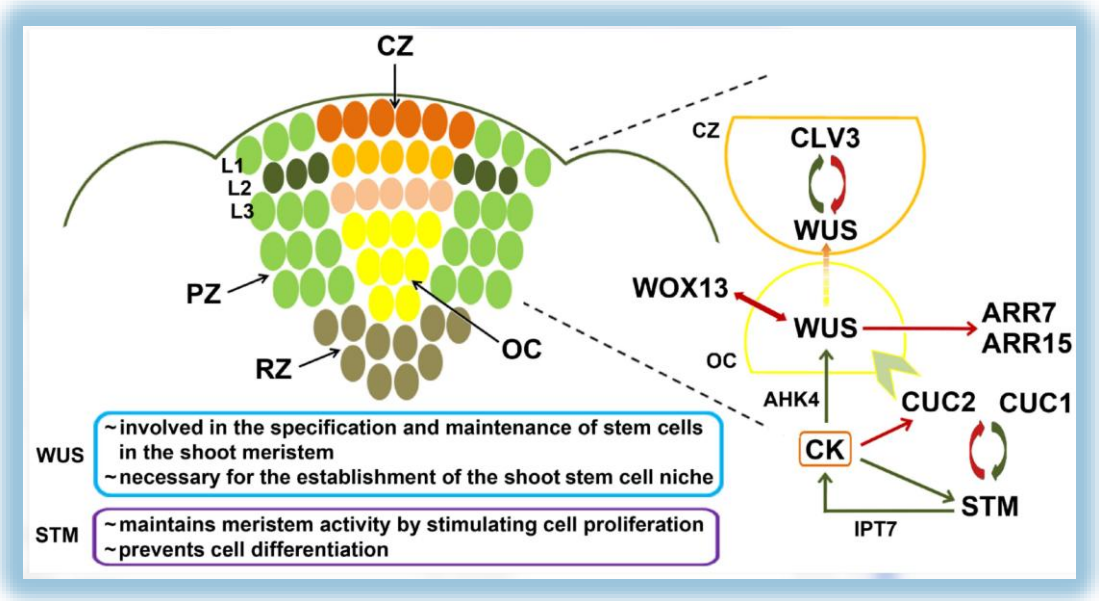
Abscisic acid (ABA) is widely recognised as an important plant stress hormone because of its essential role in regulating drought tolerance, stomatal movement, seed dormancy and various environmental stress responses. It plays a significant role in helping plants survive under unfavourable environmental conditions, particularly during periods of water scarcity. When plants experience drought or reduced water availability, the concentration of ABA generally increases in different plant tissues. This increase promotes stomatal closure, thereby reducing water loss through transpiration and helping plants maintain their internal water balance. Apart from its role in water regulation, ABA also interacts with flowering-related signalling pathways and influences the balance between vegetative growth and reproductive development. Under certain environmental conditions, drought stress may accelerate flowering as part of a drought-escape strategy, allowing some annual plant species to complete their reproductive cycle before severe water scarcity occurs. However, this response varies among plant species and depends on their genetic characteristics, developmental stages and environmental conditions. In some plants, increased ABA accumulation and prolonged drought stress may delay flowering, restrict floral development or reduce reproductive success. Therefore, ABA has a complex role in regulating flowering under changing climatic conditions. Its adaptive significance lies in helping plants respond to water scarcity, regulate the transition between vegetative and reproductive growth, support early flowering under certain drought-escape strategies and protect plant tissues against environmental stress. Understanding ABA-mediated signalling pathways is consequently important for developing crop varieties with improved drought tolerance and stable reproductive performance under changing climatic conditions.

Natural Resources for Human Health
eISSN: 2583-1194

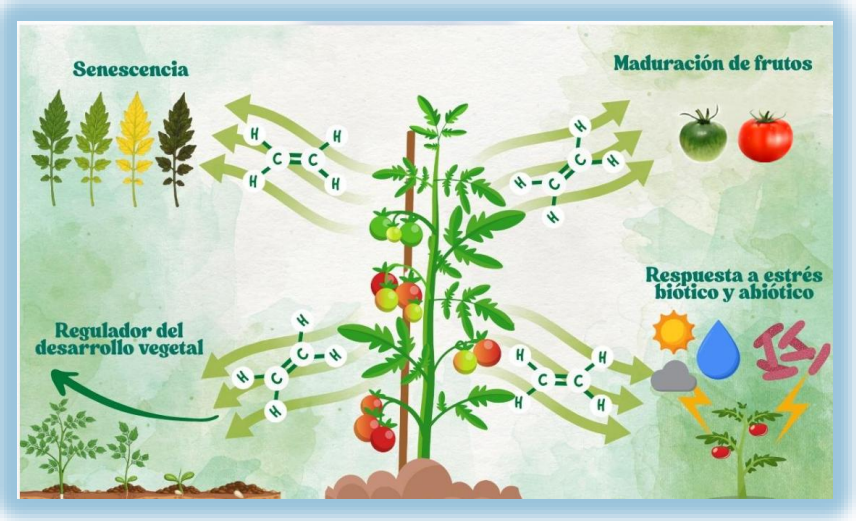


Auxins are essential plant hormones that regulate several important physiological and developmental processes, including cell elongation, vascular development, apical dominance and organ formation. Indole-3-acetic acid (IAA) is the most commonly studied naturally occurring auxin and plays a significant role in plant growth and reproductive development. During flower formation, the distribution and transport of auxin within developing floral tissues help regulate the initiation, growth and organisation of different floral organs, including petals, stamens and carpels. Auxins also interact with other plant hormones, particularly gibberellins and cytokinins, to maintain proper coordination during reproductive development. Under changing climatic conditions, environmental factors such as temperature fluctuations, excessive heat and drought may alter auxin biosynthesis, transport and distribution within plant tissues. Such changes can influence flower formation, floral organ development, pollen function and overall reproductive success. Therefore, auxin signalling represents an important component of plant adaptation to environmental stress. From an adaptive perspective, auxins support normal floral organ development, maintain coordination among different developmental processes, influence flower formation under environmental stress and interact with other hormones to regulate reproductive growth. Understanding auxin-mediated signalling mechanisms may provide valuable insights into maintaining normal flower development and improving reproductive stability in plants exposed to changing climatic conditions.

Natural Resources for Human Health
eISSN: 2583-1194



Cytokinins are important plant hormones that regulate several physiological and developmental processes, including cell division, shoot development, nutrient mobilisation and meristem activity. They play a significant role in plant growth and reproductive development by promoting cell proliferation and maintaining the activity of growing tissues. Cytokinins also contribute to the development of reproductive structures and the maintenance of floral meristems, which are responsible for the formation of flowers and their associated organs. During the transition from vegetative to reproductive growth, cytokinins interact with other plant hormones, particularly gibberellins and auxins, to coordinate developmental activities and regulate flowering processes. Under changing climatic conditions, environmental stresses such as drought and high temperature can modify cytokinin biosynthesis, transport and degradation. In certain plant species, reduced cytokinin activity under stress conditions may accelerate leaf ageing, reduce photosynthetic efficiency and influence reproductive development. However, cytokinin responses vary according to plant species, developmental stages, environmental conditions and the intensity and duration of stress. From an adaptive perspective, cytokinins regulate cell division in developing tissues, support floral meristem activity, influence reproductive growth and participate in developmental adjustments under environmental stress. Therefore, understanding cytokinin signalling and its interactions with other phytohormones is important for explaining how plants maintain flowering and reproductive development under changing climatic conditions.



Ethylene is a gaseous plant hormone that plays an important role in fruit ripening, leaf senescence, flower ageing and responses to environmental stress. It regulates several physiological processes and helps plants respond to environmental disturbances such as flooding, mechanical injury, temperature fluctuations and other unfavourable conditions. Ethylene also influences flower initiation, floral development and the process of floral senescence. Under changing climatic conditions, environmental stresses such as flooding and high temperatures may alter ethylene production and signalling in plant tissues. Excessive ethylene accumulation can accelerate flower ageing, promote premature floral senescence and cause reproductive damage in sensitive plant species. However, its effects on flowering vary among plants, as ethylene may promote particular developmental transitions in some species while delaying flowering in others. Ethylene also interacts with auxins and other phytohormones to coordinate plant growth and stress responses. From an adaptive perspective, ethylene helps plants coordinate responses to environmental stress, regulates flower development and senescence, participates in reproductive adjustments and contributes to hormonal interactions during changing environmental conditions. Therefore, understanding ethylene signalling is important for explaining the relationship between environmental stress and reproductive development in plants.

7.6 Jasmonic Acid (JA): Defence and Reproductive Balance

Jasmonic acid is an important plant signalling hormone primarily associated with defence responses against insect attacks, pathogens and environmental stresses. Apart from its protective functions, jasmonic acid also participates in reproductive development, particularly in pollen maturation, anther development and other processes essential for successful fertilisation. It helps plants regulate the balance between growth, defence and reproduction under changing environmental conditions. During periods of environmental stress, jasmonic acid signalling may influence the allocation of available resources between protective mechanisms and reproductive activities. Increased jasmonate signalling under certain conditions may modify flowering-related pathways and delay flowering, depending on the plant species and developmental stage. Its interactions with other plant hormones also contribute to the regulation of physiological and reproductive responses to environmental challenges. From an adaptive perspective, jasmonic acid strengthens plant defence against biotic stresses, influences reproductive development, regulates the balance between growth and defence and participates in hormonal signalling networks during environmental stress. Thus, jasmonic acid is an important component of plant adaptation and reproductive regulation under changing climatic conditions.

Salicylic acid is an important plant signalling molecule involved in plant immunity, disease resistance and systemic acquired resistance. It helps plants activate defence mechanisms against various pathogens and contributes to their ability to survive under biological and environmental stress conditions. In addition to its defensive functions, salicylic acid interacts with several developmental and hormonal pathways that influence flowering time and reproductive development. Changes in salicylic acid concentration and signalling activity may affect the expression of flowering-related genes and modify plant responses to environmental fluctuations. Its influence on flowering depends on several factors, including plant species, hormone concentration, developmental stage and prevailing environmental conditions. Furthermore, interactions between salicylic acid, jasmonic acid, abscisic acid and other phytohormones help coordinate plant defence and developmental responses under combined stresses. From an adaptive perspective, salicylic acid strengthens plant defence responses, interacts with other hormonal signalling pathways, influences developmental transitions and contributes to plant adaptation under combined environmental and biological stresses. Therefore, understanding salicylic acid-mediated signalling is important for examining the relationship between plant defence mechanisms, flowering regulation and reproductive adaptation under changing climatic conditions.

8. COMPARATIVE ANALYSIS OF PLANT HORMONES

Table 1. Major plant hormones and their roles in flowering regulation

Plant hormone	Major physiological function	Possible influence on flowering under stress
Gibberellins	Stem growth and floral transition	May accelerate flowering
Abscisic acid	Drought response and stomatal closure	May promote or delay flowering
Auxins	Cell elongation and floral organ formation	Modifies flower development
Cytokinins	Cell division and meristem activity	Influences floral transition

Ethylene	Stress response and senescence	May accelerate or delay flowering
Jasmonic acid	Defence and reproductive development	May delay flowering
Salicylic acid	Plant immunity and signalling	Modifies flowering-related responses

9. INFLUENCE OF CHANGING CLIMATIC CONDITIONS ON HORMONAL REGULATION

limate change influences flowering time through several environmental factors that affect the physiological, biochemical and molecular processes responsible for plant growth and reproductive development. Changes in temperature, water availability, photoperiod and seasonal conditions can modify the synthesis, transport, degradation and signalling activities of different plant hormones. These hormonal changes influence the transition from vegetative growth to reproductive development and may result in early flowering, delayed flowering, reduced flower production or reproductive failure. The responses vary among plant species depending on their genetic characteristics, environmental adaptability and developmental stages. Therefore, understanding the relationship between climate-related environmental factors and hormonal regulation is essential for explaining changes in flowering patterns under global climate change.

9.1 High-Temperature Stress

High-temperature stress is one of the major environmental factors affecting flowering time and reproductive development in plants. An increase in environmental temperature can influence the activity of different plant hormones, particularly gibberellins, abscisic acid, auxins and ethylene. In certain plant species, moderately elevated temperatures may accelerate flowering by modifying flowering-related gene expression and hormonal signalling pathways. However, prolonged exposure to excessive heat can negatively affect floral development, pollen viability, anther function, fertilisation and seed formation. Heat stress may also disturb the balance between vegetative growth and reproductive development by altering hormone biosynthesis and signalling. Abscisic acid and ethylene, in particular, participate in stress-response mechanisms that help plants adjust their physiological activities under high-temperature conditions. Similarly, changes in gibberellin and auxin signalling may influence floral initiation and the development of reproductive structures. Therefore, hormonal regulation plays an important role in determining how plants respond to elevated temperatures and maintain reproductive performance under changing climatic conditions.



Increasing temperature is one of the major environmental factors influencing flowering behaviour and reproductive development in plants. Elevated temperatures can modify the expression of flowering-related genes and influence different hormonal signalling pathways responsible for the transition from vegetative growth to reproductive development. In certain plant species, increased temperature may stimulate gibberellin biosynthesis and activate temperature-responsive signalling mechanisms, resulting in early flowering. The temperature-sensitive transcription factor PIF4 (Phytochrome Interacting Factor 4) plays an important role in thermomorphogenic responses and participates in the regulation of flowering under elevated temperature conditions. Similarly, gibberellin signalling and the degradation of DELLA proteins contribute to temperature-dependent developmental processes by regulating the activity of flowering-related transcription factors. However, the effects of increasing temperature are not always beneficial for reproductive development. Exposure to extreme heat can damage reproductive tissues, reduce pollen viability, interfere with fertilisation and negatively affect flower development. Severe heat stress may also cause flower abortion, reduce seed formation and shorten the reproductive period. The major consequences of

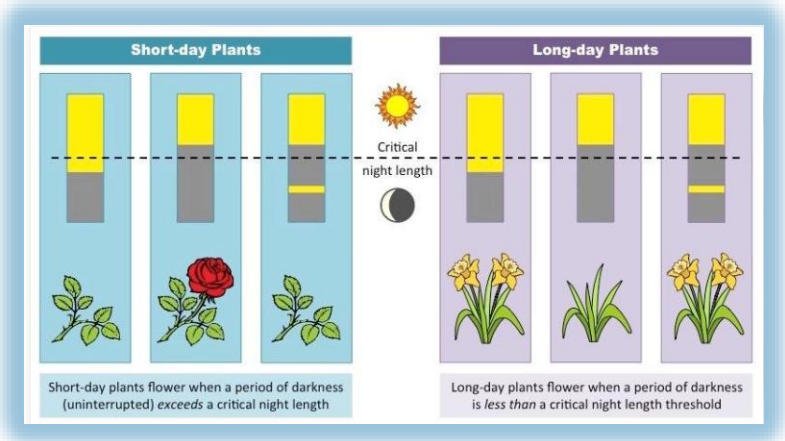
high-temperature stress include changes in flowering initiation, early flowering in temperature-sensitive plant species, reduced pollen viability, flower abortion under severe heat conditions and alterations in the duration of reproductive development. Therefore, the interaction between temperature-responsive genetic mechanisms and hormonal signalling plays a significant role in determining flowering behaviour and reproductive success under changing climatic conditions.

9.2 Drought Stress and Water Deficiency



Drought is one of the important environmental factors affecting plant growth, flowering behaviour and reproductive development. Reduced water availability can disturb several physiological and biochemical processes and influence the production and signalling activities of different plant hormones. During drought conditions, the concentration of abscisic acid (ABA) generally increases in plant tissues, activating various stress-response mechanisms that help plants conserve water and maintain cellular balance. ABA promotes stomatal closure, reduces water loss through transpiration and regulates plant responses to water deficiency. In certain plant species, drought stress may trigger an adaptive mechanism known as drought escape, in which plants flower earlier than usual and complete their reproductive cycle before severe water scarcity develops. This strategy is particularly important for annual plants growing in dry and semi-arid regions where rainfall is irregular and unpredictable. However, the effects of drought are not always favourable for flowering and reproduction. Prolonged or severe water deficiency may delay flowering, reduce flower production, interfere with pollen development, affect fertilisation and restrict seed formation. It may also alter the balance between vegetative growth and reproductive development, ultimately reducing plant productivity. Therefore, ABA-mediated stress responses and drought-escape mechanisms play important roles in determining flowering time and reproductive success under conditions of changing rainfall patterns and increasing climatic uncertainty.

9.3 Changes in Photoperiod and Light Availability



Photoperiod refers to the duration of daylight and darkness within a 24-hour period and is an important environmental signal regulating flowering time in many plant species. Plants use changes in day length to identify suitable seasons for reproductive development and to coordinate the transition from vegetative growth to flowering. On the basis of their flowering responses to day length, plants are commonly classified into three major groups: long-day plants, which generally flower when the duration of daylight exceeds a critical period; short-day plants, which generally flower when the duration of darkness is sufficiently long; and day-neutral plants, whose flowering is relatively independent of day length. The CONSTANS (CO) and FLOWERING LOCUS T (FT) signalling pathways play important roles in the molecular regulation of photoperiodic flowering. These pathways help plants recognise seasonal light signals and regulate the expression of flowering-related genes. Furthermore, photoperiodic responses interact with plant hormonal pathways, including gibberellin, auxin and cytokinin signalling, to coordinate floral initiation and reproductive development. Under changing climatic conditions, variations in temperature and seasonal environmental patterns may influence the interaction between photoperiodic signals and hormonal regulation, thereby modifying flowering behaviour in certain plant species. However, it is important to understand that climate change does not directly alter astronomical day length, which is determined by the Earth's rotation and revolution. Instead, climate change modifies temperature, rainfall and other seasonal environmental conditions that interact with the plant's photoperiodic responses. Consequently, the relationship between photoperiod and hormonal signalling is important for understanding how plants regulate flowering time and adapt their reproductive cycles to changing climatic conditions.

9.4 Irregular Rainfall and Waterlogging

Irregular rainfall is an important consequence of climate change that creates alternating periods of water deficiency and excessive soil moisture, thereby affecting normal plant growth and reproductive development. Unpredictable rainfall patterns may expose plants to repeated drought and waterlogging conditions, resulting in physiological stress and changes in hormonal regulation. Waterlogging reduces oxygen availability in the root zone and restricts normal root respiration and nutrient absorption. Under such conditions, ethylene production and signalling may increase, activating different adaptive responses that help plants tolerate excessive soil moisture. However, prolonged waterlogging can negatively affect root activity, nutrient uptake, photosynthesis and overall plant development. These physiological disturbances may also influence the production and signalling of other plant hormones, including abscisic acid, auxins and gibberellins. As a result, the balance between vegetative growth and reproductive development may be disturbed, affecting flowering initiation, flower formation and seed production. Furthermore, the combined effects of waterlogging, nutrient deficiency and hormonal imbalance may reduce reproductive efficiency and delay or modify flowering time in sensitive plant species. Therefore, understanding the relationship between irregular rainfall, ethylene-mediated stress responses and hormonal interactions is essential for explaining plant adaptation and reproductive performance under changing climatic conditions.

9.5 Elevated Atmospheric Carbon Dioxide



Increasing atmospheric carbon dioxide (CO_2) concentration is an important environmental factor that can influence plant growth, photosynthesis and reproductive development under changing climatic conditions. Elevated carbon dioxide may enhance the rate of photosynthesis in many plant species by increasing carbon assimilation and carbohydrate production. The increased availability of carbohydrates can influence sugar signalling pathways, which are associated with plant growth, developmental processes and the regulation of flowering time. Changes in carbon availability may also interact with hormonal signalling pathways, including gibberellin, auxin and cytokinin, thereby influencing the transition from vegetative growth to reproductive development. However, the relationship between elevated carbon dioxide concentration and flowering time is complex and varies according to plant species, genetic characteristics, nutrient availability, temperature and water conditions. In some plants, increased carbon dioxide may promote vegetative growth and biomass production, whereas in others, its effects on flowering initiation and reproductive development may be limited or variable. Furthermore, increased vegetative growth does not necessarily result in greater flower production, successful fertilisation or higher seed yield. Therefore, elevated carbon dioxide may provide certain growth advantages to plants, but it does not automatically guarantee earlier flowering or improved reproductive success. Understanding the interaction between carbon dioxide enrichment, carbohydrate metabolism and hormonal signalling is essential for evaluating plant adaptation and reproductive responses under future climatic conditions.

10. MOLECULAR MECHANISMS LINKING PLANT HORMONES WITH FLOWERING TIME

Flowering regulation in plants is controlled by a complex molecular network involving environmental signals, genetic mechanisms, biochemical processes and hormonal interactions. Plants perceive environmental changes such as temperature, photoperiod and water availability through specialised signalling systems, which transmit information to flowering-related genes and regulatory pathways. These molecular mechanisms coordinate the transition from vegetative growth to reproductive development and determine the appropriate timing of flowering. Several important flowering-related genes participate in this process by responding to environmental and developmental signals and regulating the expression of genes responsible for floral initiation. Their activities are also influenced by plant hormones, which help coordinate growth and reproductive responses under changing environmental conditions. Understanding these genetic and hormonal interactions is essential for explaining how plants regulate flowering time and maintain reproductive development under climate-related stresses.

CONSTANS (CO)

CONSTANS (CO) is an important flowering-related gene that regulates photoperiod-dependent flowering in plants, particularly in Arabidopsis thaliana. Its activity is controlled by the circadian clock and environmental light conditions, allowing plants to recognise seasonal changes in day length. Under inductive long-day conditions, appropriate CO protein accumulation promotes the expression of the FLOWERING LOCUS T (FT) gene in leaves. The FT protein subsequently moves through the phloem to the shoot apical meristem, where it activates flowering-related developmental processes. The CO–FT signalling pathway therefore plays a central role in connecting environmental light signals with the initiation of flowering. Changes in temperature and seasonal conditions may influence this pathway and modify flowering responses in different plant species. Consequently, CONSTANS is an important molecular regulator for understanding how plants coordinate flowering time with environmental conditions.

FLOWERING LOCUS C (FLC)

FLOWERING LOCUS C (FLC) is an important flowering-repressor gene that regulates the timing of reproductive development in plants. It prevents premature flowering by suppressing the expression of flowering-promoting genes, particularly FT and SOC1, under certain environmental and developmental conditions. In many winter-annual plants, FLC expression is initially high and inhibits flowering during unfavourable seasonal conditions. Vernalisation, which refers to prolonged exposure to low temperatures, gradually reduces FLC expression through epigenetic regulation. This reduction allows flowering-promoting pathways to become active when other environmental conditions are favourable. The FLC pathway therefore plays an essential role in seasonal flowering regulation by ensuring that plants experience an appropriate period of cold before initiating reproductive development. Under changing climatic conditions, alterations in winter temperature and the duration of cold exposure may influence vernalisation requirements and FLC activity, potentially modifying flowering time. Thus, FLC is an important genetic component in understanding plant adaptation to changing seasonal temperature patterns.

Natural Resources for Human Health
eISSN: 2583-1194

SOC1 and LFY

SUPPRESSOR OF OVEREXPRESSION OF CONSTANS 1 (SOC1) and LEAFY (LFY) are important flowering-related genes that regulate the transition from vegetative growth to reproductive development. SOC1 functions as an important integrator of flowering signals received through photoperiod, temperature, vernalisation and hormonal pathways. It coordinates information from different regulatory mechanisms and promotes the activation of downstream genes responsible for floral transition. LEAFY (LFY), on the other hand, plays a significant role in establishing floral meristem identity and initiating the development of floral structures. It helps determine whether developing meristems produce flowers rather than vegetative structures. The coordinated activities of SOC1 and LFY ensure the proper initiation and development of reproductive organs. Environmental changes, including temperature fluctuations and water stress, may indirectly influence their expression through interactions with flowering-related genetic and hormonal pathways. Therefore, these genes are essential components of the molecular network controlling flowering time, floral development and reproductive adaptation under changing climatic conditions.

Table 2. Important molecular components associated with flowering regulation

Molecular component	Major role	Environmental connection
FT	Promotes flowering	Photoperiod and temperature
CO	Regulates FT expression	Light and circadian signals
FLC	Represses flowering	Vernalisation and temperature
SOC1	Integrates flowering signals	Environmental and hormonal signals
LFY	Floral meristem identity	Developmental signalling
PIF4	Temperature-responsive regulation	High-temperature conditions
DELLA	Represses GA signalling	Gibberellin and temperature responses

11. HORMONAL CROSSTALK: AN INTEGRATED ADAPTIVE MECHANISM

One of the most important mechanisms involved in plant adaptation to changing environmental conditions is hormonal crosstalk. Hormonal crosstalk refers to the interaction between two or more plant hormone signalling pathways, through which different hormones coordinate their activities to regulate plant growth, development, stress responses and reproduction. These interactions play a significant role in determining flowering time and maintaining reproductive development under environmental stress. For example, during drought conditions, abscisic acid (ABA) signalling generally increases to promote stomatal closure and conserve water. At the same time, changes in gibberellin signalling may influence plant growth, developmental processes and the transition from vegetative to reproductive development. Similarly, auxins and cytokinins interact to regulate cell division, floral meristem activity and the development of floral organs. Gibberellins also interact with other hormonal pathways to influence flowering initiation under favourable environmental conditions. Furthermore, jasmonic acid and salicylic acid participate in defence-related signalling and help plants coordinate protective responses against insects, pathogens and environmental stresses. Ethylene also interacts with auxin, ABA and other phytohormones to regulate stress adaptation, flower development and reproductive processes. These hormonal interactions are not always independent or uniform; they may produce synergistic or antagonistic effects depending on plant species, developmental stages and environmental conditions. Therefore, hormonal crosstalk provides an important regulatory mechanism through which plants balance vegetative growth, reproductive development, defence and survival. Understanding these interconnected signalling pathways is essential for explaining how plants maintain flowering stability and reproductive success under changing climatic conditions.

Table 3. Examples of hormonal interactions under environmental stress

Hormonal interaction	Major response	Possible developmental outcome
ABA–GA	Growth and stress-response balance	Changes in flowering time
Auxin–Cytokinin	Cell division and organ development	Floral development

GA–Ethylene	Growth and stress signalling	Changes in reproductive growth
JA–SA	Defence signalling interaction	Resource allocation changes
ABA–Ethylene	Drought and waterlogging responses	Developmental adjustment

12. PROPOSED CONCEPTUAL MODEL: CLIMATE-RESPONSIVE HORMONAL ADAPTATION

The present paper proposes an integrated conceptual model to explain the relationship between climate conditions, phytohormones and flowering time.

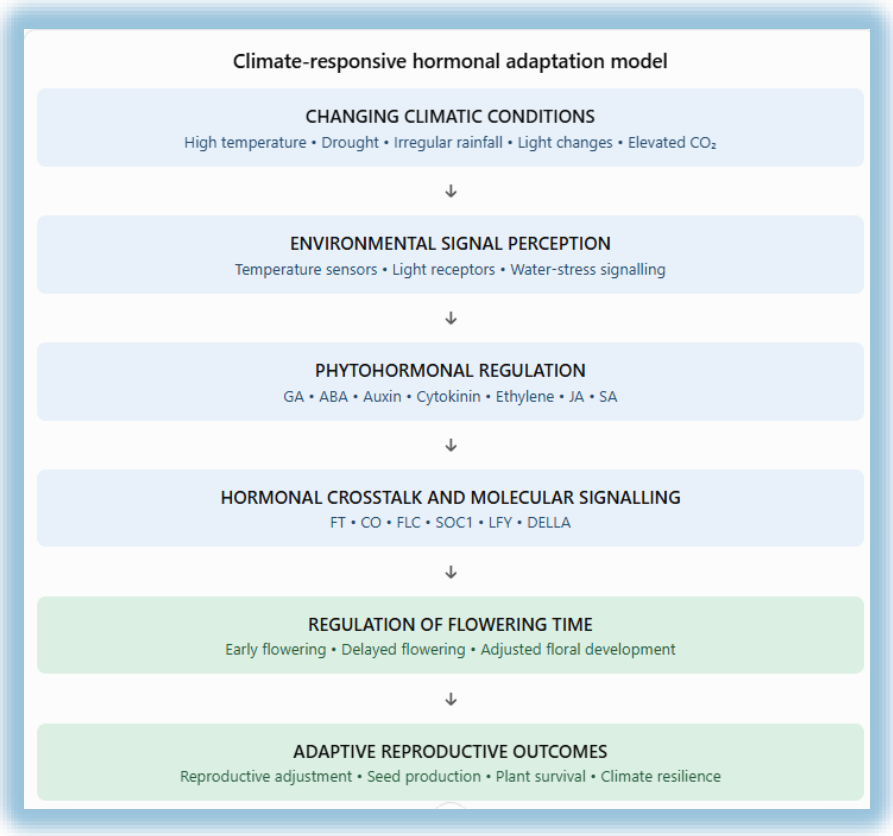


Figure 1. Proposed conceptual framework showing the interaction between climatic signals, hormonal networks and flowering regulation.

The proposed conceptual framework explains how plants perceive environmental changes and activate different physiological, biochemical and molecular signalling mechanisms to regulate flowering time. Environmental factors such as increasing temperature, drought, irregular rainfall, photoperiodic conditions and elevated atmospheric carbon dioxide act as external signals that influence plant growth and reproductive development. In response to these environmental changes, plants modify the synthesis, transport and signalling activities of different phytohormones, including gibberellins, abscisic acid, auxins, cytokinins, ethylene, jasmonic acid and salicylic acid. These hormonal changes interact through complex signalling networks and influence the expression of flowering-related genes such as FT, CO, FLC, SOC1 and LFY. The combined activities of these hormonal and molecular pathways determine the timing of floral initiation, floral development and reproductive transition. Depending on the intensity, duration and nature of environmental stress, plants may modify their flowering schedules through mechanisms such as early flowering, delayed flowering or adjustments in reproductive development to improve their chances of successful reproduction. The proposed framework highlights the relationship between environmental signals, hormonal interactions and genetic regulation of flowering. It also provides a scientific foundation for future experimental

investigations into the mechanisms of hormonal adaptation, flowering regulation and plant reproductive resilience under changing climatic conditions.

13. DISCUSSION

The relationship between plant hormones and flowering time is complex and is influenced by several factors, including environmental conditions, genetic background and the developmental stage of the plant. Different phytohormones perform specific functions in regulating flowering, but their combined interactions determine the overall reproductive response under changing climatic conditions. Gibberellins are particularly important because they directly participate in the transition from vegetative growth to reproductive development in several plant species. Their interaction with DELLA proteins provides an important molecular mechanism connecting hormonal signalling with flowering regulation. Abscisic acid (ABA) has a different but equally significant role in plant adaptation, particularly under drought conditions. It helps plants conserve water, activate stress-response mechanisms and modify reproductive timing through stress-related developmental pathways.

Similarly, auxins and cytokinins play important roles in floral meristem development, cell division and the formation of reproductive organs. Ethylene, jasmonic acid and salicylic acid contribute to environmental stress signalling and may indirectly influence flowering through their interactions with other hormonal pathways. These hormonal interactions demonstrate that flowering regulation is not controlled by a single hormone but involves a coordinated network of physiological, biochemical and molecular mechanisms.

An important observation from the available scientific literature is that plants do not respond uniformly to climate-related environmental stress. Their responses vary according to species, genetic characteristics, developmental stages and the intensity and duration of environmental disturbances. Some plants accelerate flowering under unfavourable conditions as a drought-escape or stress-avoidance strategy, whereas others delay flowering to maintain vegetative growth or wait for more favourable environmental conditions. Research on the genetic and epigenetic regulation of flowering has further strengthened the understanding of hormonal control of floral transition. Studies such as Li et al. (2024) highlight the importance of hormonal crosstalk and regulatory mechanisms in controlling flowering-related developmental processes. Similarly, research on environmental regulation of flowering demonstrates that temperature, light conditions and water availability interact with internal genetic and developmental mechanisms to determine flowering behaviour.

A further important consideration is that flowering initiation and successful reproduction are two different biological processes. A plant may initiate flowering earlier under high-temperature conditions, but excessive heat may reduce pollen viability, interfere with fertilisation and negatively affect seed development. Therefore, early flowering should not automatically be considered a successful adaptive response. This distinction is particularly important in agricultural crops because flowering time directly influences pollination, fruit formation, seed development and final crop productivity. Even when plants successfully initiate flowering under stressful environmental conditions, their reproductive performance may decline because of unfavourable climatic conditions.

Overall, the available scientific literature indicates that hormonal adaptation is a coordinated process involving environmental perception, hormonal signalling, genetic regulation and reproductive development. The interactions among different phytohormones enable plants to adjust their flowering schedules in response to changing environmental conditions. A better understanding of these mechanisms may contribute to the development of climate-resilient crop varieties with improved flowering stability, reproductive efficiency and agricultural productivity.

14. APPLICATIONS IN CLIMATE-RESILIENT AGRICULTURE

14. Practical Applications of Hormonal Regulation of Flowering

Understanding the hormonal mechanisms involved in flowering regulation has several important applications in agriculture, plant biotechnology, crop improvement and biodiversity conservation. Knowledge of hormonal signalling pathways and flowering-related genes can help researchers and agricultural scientists develop strategies to improve plant adaptation and reproductive performance under changing climatic conditions.

14.1 Development of Climate-Resilient Crop Varieties

Understanding the relationship between plant hormones and flowering-related genes provides valuable opportunities for developing climate-resilient crop varieties. Plant breeders can use information about gibberellin, abscisic acid and other hormonal pathways to identify crop varieties capable of maintaining suitable flowering periods under changing temperature and rainfall conditions. The selection of plants with stable flowering behaviour, improved pollen viability and better reproductive performance may help reduce crop losses associated with climate-related stresses. Such approaches can contribute to maintaining agricultural productivity under unpredictable environmental conditions.

14.2 Hormone-Based Crop Management

Plant growth regulators have considerable potential for managing flowering and reproductive development in selected agricultural crops. Appropriate application of hormonal substances may help regulate floral initiation, flowering duration, fruit development and reproductive performance. For example, gibberellins and other plant growth regulators are used in certain crop-management practices to influence specific developmental processes. However, their effectiveness depends on crop species, developmental stage, environmental conditions, application methods and suitable concentrations. Therefore, crop-specific experimental investigations and careful timing are essential before recommending hormone-based management practices.

14.3 Drought-Resistant Agriculture

Understanding abscisic acid (ABA) signalling and its interactions with other plant hormones may support the development of agricultural strategies for improving drought tolerance. ABA plays an important role in regulating stomatal closure, water conservation and stress-response mechanisms. Studying ABA-mediated pathways may help researchers identify crop varieties capable of maintaining growth and reproductive development under limited water availability. Furthermore, understanding the relationship between drought responses and flowering time may support the selection of crops that can complete their reproductive cycles under irregular rainfall conditions. These approaches are particularly valuable for agricultural regions frequently affected by water scarcity.

14.4 Molecular Breeding and Genetic Engineering

Advances in molecular biology and agricultural biotechnology have created new opportunities for investigating the genetic mechanisms responsible for flowering regulation. Modern techniques such as CRISPR-based gene editing, transcriptome analysis and molecular marker-assisted selection can help researchers study and modify flowering-related genes and their interactions with hormonal signalling pathways. Genes such as FT, CO, FLC and SOC1 are important targets for investigating the molecular regulation of floral transition. Such approaches may contribute to the development of crop varieties with desirable flowering characteristics, improved environmental adaptability and greater reproductive stability. However, the effectiveness and agricultural suitability of these genetic modifications require careful experimental evaluation.

14.5 Conservation of Plant Biodiversity

Understanding climate-related changes in flowering time is also important for the conservation of natural vegetation and biodiversity. Changes in temperature, rainfall and seasonal environmental conditions may alter the flowering periods of wild plant species, affecting their interactions with pollinators, seed-dispersing organisms and other ecological components. Differences between flowering periods and pollinator activity may disturb plant–pollinator relationships and influence successful seed production and natural regeneration. Studying the hormonal mechanisms responsible for flowering responses can therefore improve scientific understanding of plant adaptation to climate change. This knowledge may contribute to biodiversity conservation, ecological restoration and sustainable management of natural ecosystems.

15. INNOVATIVE RESEARCH SCOPE AND FUTURE DIRECTIONS

Table 4. Future research opportunities

Research area	Suggested investigation	Expected contribution
Hormonal profiling	Measure GA, ABA, IAA and cytokinin under different temperatures	Understand hormonal variation

Drought experiments	Compare flowering time under different water regimes	Identify drought-adaptive responses
Heat experiments	Study flowering under controlled temperature treatments	Identify heat-responsive mechanisms
Gene expression	Analyse FT, CO, FLC and SOC1 expression	Understand molecular regulation
Hormonal crosstalk	Study combined effects of ABA and GA	Explain integrated adaptation
Crop comparison	Compare flowering responses among crop varieties	Identify climate-resilient varieties
Field experiments	Monitor flowering across different seasonal conditions	Establish ecological relevance

15.1 Suggested Original Experimental Design

To extend the present review into an original laboratory-based research study, a controlled experiment is proposed to investigate the role of plant hormones in regulating flowering time under changing climatic conditions. The experiment may be conducted using Arabidopsis thaliana as a model plant or mung bean (Vigna radiata) as a locally available crop species. Plants should be grown under controlled environmental conditions and divided into five treatment groups. The control group (T0) will be maintained at normal temperature with regular watering. Treatment T1 will be exposed to elevated temperature, while T2 will receive moderate drought stress. Treatment T3 will be subjected to a combination of elevated temperature and moderate drought. Treatment T4 will receive elevated temperature with suitable watering and an appropriately selected plant hormone treatment. The experiment should include at least three independent biological replicates for each treatment, with a sufficient number of plants in each replicate to ensure reliable observations. Temperature, watering levels, hormone concentration, application method and treatment duration should be clearly defined before the experiment begins.

The major growth, flowering and reproductive parameters should be recorded systematically throughout the experimental period. These parameters will include the number of days required for the appearance of the first flower, the number of flowers produced per plant, plant height at flowering, number of branches, percentage of flower abortion and fruit or pod formation. Reproductive performance may further be evaluated by recording seed number and seed weight. In addition, chlorophyll content should be measured to assess the physiological condition of plants under different environmental treatments. The concentrations of abscisic acid (ABA) and gibberellins (GA) should also be estimated to understand changes in hormonal balance. At the molecular level, the expression of important flowering-related genes, particularly FT, CO and SOC1, may be examined using suitable gene-expression techniques such as quantitative real-time PCR (qRT-PCR).

The collected experimental data should be analysed using appropriate statistical methods. Mean and standard deviation can be calculated to describe the observations, while analysis of variance (ANOVA) can be applied to determine whether significant differences exist among the treatment groups. Tukey's post-hoc test may be used for comparisons between individual treatments when the assumptions of the selected ANOVA procedure are satisfied. Pearson correlation can help identify associations between hormone concentrations and flowering time, while regression analysis may be used to examine the relationship between environmental stress, hormonal changes and flowering responses. A combined analysis of hormone levels and flowering-related gene expression may provide further insight into the physiological and molecular mechanisms involved in flowering regulation.

This proposed experimental design could provide a systematic approach to understanding how elevated temperature and drought conditions influence hormonal balance, flowering initiation and reproductive performance. It may also help identify whether suitable hormone treatments can reduce the adverse effects of environmental stress on flowering and crop productivity. However, the proposed design represents a plan for future experimental investigation. No laboratory observations, experimental results, statistical values or treatment effects are claimed in the present review paper. Actual conclusions can be drawn only after conducting the experiment and analysing the collected data.

16. CONCLUSION

Plant hormones play a fundamental role in regulating flowering time and helping plants respond to changing environmental conditions. Climate change, particularly increasing temperatures, irregular rainfall, drought and other environmental disturbances, can influence the timing and success of plant reproduction.

The present review demonstrates that gibberellins, abscisic acid, auxins, cytokinins, ethylene, jasmonic acid and salicylic acid participate in the regulation of plant growth and reproductive development. Their activities are interconnected through complex hormonal signalling networks.

Gibberellins are important regulators of floral transition, while abscisic acid plays a major role in drought responses. Auxins and cytokinins contribute to floral organ development, whereas ethylene, jasmonic acid and salicylic acid participate in environmental stress responses and reproductive regulation.

The interaction of these hormones with flowering-related genes such as FT, CO, FLC and SOC1 provides an important molecular basis for understanding climate-responsive flowering behaviour.

An important conclusion is that flowering-time adaptation is not controlled by a single hormone. Instead, it results from the coordinated interaction of environmental signals, hormonal balance, genetic regulation and plant developmental processes.

The proposed climate-responsive hormonal adaptation model provides a conceptual foundation for understanding these relationships. Further experimental studies involving hormonal profiling, molecular analysis and controlled environmental treatments are necessary to validate the proposed framework.

Ultimately, a better understanding of phytohormonal regulation may support the development of climate-resilient crops, improve reproductive stability, protect plant biodiversity and contribute to sustainable agricultural production under changing climatic conditions.

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