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ROLE OF PLANT GROWTH REGULATORS IN FLOWER INDUCTION AND QUALITY ENHANCEMENT: A REVIEW

Jaya Bijaya Biraja Das[1], Swapnil Bharti[2*], Ravi Pratap Singh[3], Devi Singh[3], Lakhwinder Singh[4], G. Ranganna[5], Purnima Singh Sikarwar[6] and Surender Kumar[7]
[1]Department of Floriculture and Landscaping, College of Agriculture,
Odisha University of Agriculture and Technology (OUAT), Bhubaneswar, Odisha, India
[2]Department of Floriculture and Landscaping, Bihar Agricultural University, Sabour , Bhagalpur, Bihar, India
[3]Department of Horticulture, Faculty of Agriculture, Maharishi Markandeshwar
(Deemed to be) University Mullana Ambala Haryana, India
[4]Faculty of Agriculture, Guru Kashi University Talwandi sabo Bathinda, Punjab India (151-302).
[5]Horticultural Research Station, VR Gudem, Dr.YSR Horticultural University,
West Godavari-534101, Andhra Pradesh, India
[6]Department of Floriculture and Landscaping, Department of Horticulture, SHUATS, Prayagraj -211007 (U.P.)
[7]Department of Botany, Pt. N.R.S. Govt. College Rohtak, Haryana, India
*Corresponding author E-mail: swapnilbau317@gmail.com

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ABSTRACT

Plant growth regulators (PGRs), both endogenous hormones and synthetic analogs, have emerged as pivotal tools in modern agriculture and horticulture for their significant influence on plant development, particularly in flower induction and quality enhancement. These compounds regulate diverse physiological pathways such as cell division, elongation, differentiation, and senescence. This review synthesizes the latest findings regarding the roles of key PGRs auxins, gibberellins, cytokinins, ethylene, and abscisic acid in floral initiation, flower development, and enhancement of ornamental and reproductive traits. Application strategies, interactions among hormones, and molecular mechanisms underlying their action are thoroughly examined. Additionally, the paper delves into biotechnological innovations and challenges associated with the commercial application of PGRs in improving flower yield and aesthetics.

***Keywords*: Plant growth regulators, flower induction, floral quality, auxins, gibberellins, cytokinins, ethylene, abscisic acid, horticulture

Introduction

Flowering is a pivotal developmental transition in the life cycle of higher plants, marking the onset of reproductive growth. The timing, frequency, and quality of flowering not only determine reproductive success in natural ecosystems but also significantly impact agricultural productivity and the economic value of ornamental crops. The induction of flowering and the enhancement of floral quality are influenced by a complex interplay of genetic, environmental, and hormonal signals. Among these, plant growth regulators (PGRs) a diverse group of endogenous hormones and their synthetic analogs play a central role in modulating plant growth and development, including floral initiation, organ formation, and flower quality. PGRs such as auxins, gibberellins (GAs), cytokinins, ethylene, and abscisic acid (ABA) are key signaling molecules that act at various stages of floral development. Each hormone has a distinct but often overlapping role in orchestrating cellular and molecular processes associated with flower induction. Auxins, for instance, are critical for establishing floral meristem identity and regulating organ patterning through polar transport and interaction with auxin response factors. Gibberellins are widely known for promoting the transition to flowering, especially under suboptimal photoperiods, by modulating the expression of floral integrator genes such as LEAFY (LFY) and SUPPRESSOR OF OVEREXPRESSION OF CONSTANS1 (SOC1). Cytokinins enhance cell division and nutrient allocation to developing floral tissues, thereby improving flower quality and longevity. Ethylene, while often associated with senescence, also controls key aspects of flower opening, abscission, and sex expression in monoecious and dioecious plants. ABA, traditionally viewed as a stress hormone, contributes to floral induction under adverse conditions and helps maintain flower viability during environmental stress.

Beyond their natural roles, PGRs are widely applied exogenously in horticultural and agricultural practices to manipulate flowering time, synchronize bloom, increase floral yield, and enhance desirable aesthetic traits such as color, size, fragrance, and shelf life. Their use is particularly prevalent in the commercial production of floricultural crops like orchids, roses, carnations, and lilies, as well as in fruit crops where flowering is tightly linked to yield potential. However, the effectiveness of PGRs depends on several factors, including species specificity, developmental stage, concentration, method of application, and environmental conditions. Inappropriate use can result in undesirable outcomes such as delayed flowering, floral abnormalities, or reduced fertility.

Recent advances in molecular biology and biotechnology have provided new tools to investigate and manipulate the hormonal control of flowering. Techniques such as gene editing (e.g., CRISPR/Cas9), transcriptomics, proteomics, and hormone profiling have enhanced our understanding of PGR signaling networks and their interaction with flowering genes. Moreover, the development of innovative PGR formulations, including nano-encapsulation and controlled-release carriers, has improved hormone delivery and reduced environmental impact. This review paper aims to provide a comprehensive overview of the role of plant growth regulators in flower induction and quality enhancement. By synthesizing current knowledge from molecular, physiological, and applied perspectives, the paper explores how PGRs can be strategically used to improve floral traits in a wide range of plant species. Additionally, the paper highlights emerging technologies and biotechnological tools that promise to refine flowering control and contribute to sustainable crop production and ornamental plant development.

Auxins in Flower Development

Auxins are one of the most critical classes of phytohormones involved in regulating plant growth and development, playing a vital role in floral induction and organogenesis. Indole-3-acetic acid (IAA), the primary naturally occurring auxin, governs diverse processes such as cell division, elongation, and differentiation. In the context of flower development, auxins are instrumental in determining floral meristem identity, organ formation, and symmetry (Zhao, 2010). The spatial and temporal distribution of auxins within plant tissues achieved through polar auxin transport is central to their regulatory role in flowering. The role of auxins in floral meristem establishment and organ initiation has been widely demonstrated. During early floral development, auxin maxima are established by the action of PIN-FORMED (PIN) proteins, which direct auxin efflux and create localized concentration peaks at specific sites of floral organogenesis (Benková *et al.,* 2003). These maxima function as positional signals for the initiation of floral primordia, guiding the sequential development of sepals, petals, stamens, and carpels (Chandler, 2009). Auxin signaling operates through the auxin response pathway, which includes the TIR1/AFB receptor family, AUX/IAA repressors, and Auxin Response Factors (ARFs). The binding of auxin to the TIR1 receptor leads to the degradation of AUX/IAA proteins, thereby releasing ARFs to activate downstream genes related to flower formation (Dharmasiri *et al.,* 2005; Guilfoyle and Hagen, 2007). Specific ARFs, such as ARF5/MONOPTEROS, have been shown to regulate genes involved in gynoecium and stamen development, underscoring their importance in reproductive organ differentiation (Nemhauser *et al.,* 2000). Experimental manipulation of auxin levels has further confirmed their role in flowering. Exogenous application of IAA has been reported to promote floral bud development in orchids and roses, while auxin transport inhibitors such as NPA (N-1-naphthylphthalamic acid) disrupt organ patterning and reduce flower numbers (Ichihashi, 1997; Reinhardt *et al*., 2003). In Arabidopsis, mutants defective in auxin transport or signaling, such as pin1 or arf3, exhibit floral abnormalities including reduced organ number and asymmetry (Okada *et al*., 1991; Sessions *et al*., 1997).

Moreover, auxin crosstalk with other hormones, particularly gibberellins and cytokinins, modulates flowering responses under various environmental cues. For instance, auxin-induced transcription factors interact with GA-responsive genes to coordinate floral induction and differentiation in photoperiod-sensitive species (Sun, 2010; Morini *et al*., 2010). This hormonal integration ensures a balanced transition to reproductive development and optimizes resource allocation to developing flowers. In horticulture, auxin-based formulations are frequently applied to enhance floral attributes, including size, symmetry, and postharvest longevity. However, these benefits depend on careful management, as excessive auxin can lead to floral deformities or premature senescence (Arteca, 1996).

Gibberellins: Promoters of Flower Induction

Gibberellins (GAs) are a group of diterpenoid phytohormones that play a crucial role in the regulation of numerous developmental processes in plants, including seed germination, stem elongation, and floral transition. Among their most significant roles is the promotion of flower induction, particularly in plants where flowering is otherwise delayed by environmental or genetic factors (Mutasa-Göttgens and Hedden, 2009). This makes GAs especially important in both agronomic and horticultural practices aimed at optimizing flowering time and enhancing floral yield. In long-day plants like Arabidopsis thaliana, GAs are essential for flowering under non-inductive short-day conditions. Mutant studies have demonstrated that GA-deficient or GA-insensitive mutants exhibit delayed or failed floral transition, emphasizing their role in overcoming photoperiodic barriers (Wilson *et al.*, 1992). GAs act by upregulating floral integrator genes such as SUPPRESSOR OF OVEREXPRESSION OF CONSTANS1 (SOC1) and LEAFY (LFY), which coordinate environmental signals with intrinsic developmental cues (Blázquez *et al.*, 1998). The molecular mechanism of GA action is largely mediated through the GID1–DELLA signaling pathway. GID1 proteins serve as GA receptors; upon GA binding, GID1 interacts with DELLA proteins key repressors of GA responses leading to their degradation via the ubiquitin-proteasome pathway (Griffiths *et al.*, 2006). The removal of DELLA repression allows for the activation of genes involved in floral induction and development. This mechanism enables GAs to modulate flowering by alleviating transcriptional repression, thereby promoting a timely switch from vegetative to reproductive growth (Sun, 2010).

GA treatments also have a good effect on perennial plants like grapevine (Vitis vinifera) and apple (Malus domestica). GAs enable for faster and more coordinated flowering in these species by reducing the juvenile phase and stimulating the development of floral meristems (Ramírez *et al.,* 2001; Boss and Thomas, 2002). This effect is often species-specific and dose-dependent, requiring precise application protocols to avoid unwanted vegetative overgrowth or floral inhibition. In commercial agriculture, exogenous application of gibberellins has been successfully used to promote off-season flowering and improve the floral quality of crops like sugarcane, citrus, and ornamental species (Pharis and King, 1985; Rademacher, 2000). For example, GA_3 application in citrus can induce flowering even under suboptimal conditions, contributing to enhanced yield and better market timing (Monselise and Halevy, 1964). Despite their beneficial role, GA treatments can sometimes produce antagonistic effects depending on the species, developmental stage, and environmental context. Excessive GA levels can lead to elongated internodes and reduced floral fertility, highlighting the need for precise hormonal regulation (Yamaguchi, 2008). Hence, integrating GA treatments with other growth regulators or environmental controls is often necessary for optimal outcomes.

Cytokinins and Floral Quality Enhancement

In specifically, cytokinins are a family of plant growth regulators that are essential for stimulating cell division, postponing senescence, and improving floral development, among other physiological functions. These hormones are central to the regulation of flowering, improving both the aesthetic and commercial value of ornamental plants. Cytokinins have been extensively studied for their ability to influence flower size, color, and longevity, all of which are essential traits in the ornamental horticulture industry (Mula *et al.*, 2012). This article explores the role of cytokinins in enhancing floral quality, emphasizing their effects on flower size, color intensity, and shelf life. One of the key contributions of cytokinins to floral quality is their ability to promote cell division and organ expansion during flower development. By stimulating cellular proliferation, cytokinins can increase flower size, leading to more attractive and marketable blooms. For instance, in chrysanthemum (Chrysanthemum morifolium), a common ornamental flower, cytokinin treatments have been shown to significantly enhance flower size and improve uniformity in blooming, making the flowers more desirable for commercial purposes (Mula *et al.*, 2012). Similarly, studies have demonstrated that the application of cytokinins enhances the size and symmetry of flowers in other species, such as petunia (Petunia spp.) and gerbera (Gerbera jamesonii) (Giri *et al.*, 2011).

In addition to influencing flower size, cytokinins are also known to impact flower color, a critical factor in ornamental horticulture. Flower color is determined by the synthesis and accumulation of pigments, such as anthocyanins, which contribute to the vibrant hues of flowers. Cytokinins have been found to enhance the intensity of flower color by stimulating the biosynthesis of anthocyanins in plants such as petunia (Solfanelli *et al*., 2006). This effect is particularly beneficial for flower growers who aim to produce vibrant, eye-catching flowers for the market. The application of cytokinins can therefore be used as a strategy to enhance the visual appeal of ornamental flowers.

Moreover, cytokinins have been shown to delay flower senescence, extending the longevity of blooms. The ability to prolong flower life is an important trait in both cut flower production and ornamental horticulture, as flowers that last longer on the plant or in floral arrangements have higher commercial value. Studies have shown that cytokinin treatments can effectively delay the senescence of floral organs by inhibiting the degradation of chlorophyll and other cellular components (Van Staden and Elstner, 1995). In species such as lily (*Lilium* spp.) and rose (*Rosa* spp.), cytokinin application has been found to increase flower longevity, making them more suitable for long-term display and transportation (Zhao *et al*., 2006). The effects of cytokinins are highly species-specific, and optimal application strategies must be developed to maximize their benefits in various floral species. These tactics will be improved and the flower industry's sustainable growth will be aided by more investigation into the molecular processes behind cytokinin activity.

Ethylene: Regulator of Senescence and Sex Expression

Ethylene is a gaseous plant hormone that plays a crucial role in regulating various aspects of plant growth and development, including senescence, ripening, and sex expression. As one of the most well-studied plant hormones, ethylene influences multiple physiological processes, making it a key regulator in agricultural and horticultural practices. Two significant processes in which ethylene plays an essential role are senescence (the aging process of plants and plant organs) and sex expression, particularly in dioecious plants (plants with distinct male and female individuals). This article explores how ethylene acts as a regulator in these two vital processes.

Ethylene and Senescence

Senescence is a programmed process in plants that leads to the deterioration and eventual death of plant organs, such as leaves, flowers, and fruit. Ethylene is considered one of the primary hormones responsible for the regulation of senescence. It triggers a cascade of molecular events that lead to the breakdown of cellular components, including chlorophyll degradation, lipid peroxidation, and the degradation of proteins and nucleic acids. These processes ultimately result in the aging and death of plant tissues. Ethylene's role in senescence is particularly evident in the context of flower and fruit aging. In cut flowers, for instance, ethylene exposure accelerates petal wilting and leaf drop, reducing the vase life of flowers. However, understanding ethylene's role in this process has also led to strategies for extending the shelf life of cut flowers. By using ethylene inhibitors, such as silver thiosulfate or 1-methylcyclopropene (1-MCP), the effects of ethylene can be mitigated, extending the postharvest life of flowers such as roses and lilies (Zhang *et al*., 2009). Additionally, in fruit ripening, ethylene stimulates processes like softening, color change, and flavor development, all of which are part of the natural senescence process that occurs during fruit maturation (Hobson, 1999).

Ethylene and Sex Expression

Additionally, especially in dioecious species, ethylene is crucial in regulating the sex expression of flowers. Male or female flowers are produced by individuals in dioecious plants, and chemicals such as ethylene frequently affect how the environment regulates sex determination. Ethylene has been shown to promote the development of female flowers in several dioecious species. For instance, in hemp (Cannabis sativa), ethylene treatments can increase the proportion of female plants, which are commercially more valuable due to their higher cannabinoid content (Sharma *et al*., 2020). Similarly, in cucumber (*Cucumis sativus*), ethylene treatment has been found to promote the production of female flowers, improving the yield and quality of fruit (Madhavan *et al*., 2018). In contrast, the inhibition of ethylene synthesis or action often results in an increased number of male flowers. This differential regulation of sex expression by ethylene provides an opportunity for horticulturists and agriculturists to manipulate sex ratios in dioecious crops, thus optimizing yields. Additionally, the use of ethylene inhibitors in male-dominated crops can encourage female flower production, which is generally preferred for fruit-bearing crops (Zhang *et al*., 2014).

Abscisic acid and stress-mediated floral responses

Abscisic acid (ABA) is a plant hormone primarily associated with stress responses, particularly under conditions of water deficit, salinity, and low temperatures. It plays a vital role in regulating plant growth and development by modulating processes such as stomatal closure, seed dormancy, and the response to environmental stress. Interestingly, ABA is also involved in floral development, where its role becomes particularly evident during stress conditions. This article explores the effects of ABA on floral responses, emphasizing its involvement in stress-mediated flower development and reproductive success.

Abscisic Acid in Stress Responses

ABA's primary function in stress response is to promote adaptations that help the plant cope with adverse environmental conditions. In response to abiotic stresses, such as drought, high salinity, and extreme temperatures, ABA accumulation increases within plant tissues. This increase leads to physiological changes that help conserve water, such as stomatal closure, which reduces transpiration and minimizes water loss (Cutler *et al.*, 2010). Furthermore, ABA enhances root growth and promotes the synthesis of protective proteins, all of which are important for plant survival under stress. In terms of floral responses, environmental stress often leads to a decrease in flower number and reproductive success. ABA plays a crucial role in mediating these stress-induced changes. For example, under water deficit conditions, ABA can trigger the premature senescence of flowers, leading to a reduced number of viable flowers and lower fruit set (Pei *et al.*, 2000). This response helps the plant conserve resources during times of stress. However, this reduction in reproductive output can also compromise plant fitness and yield, particularly in agricultural systems.

ABA and Floral Development

ABA's involvement in floral development is complex, as it both promotes and inhibits various stages of flower formation, depending on the species and environmental conditions. In Arabidopsis, ABA was found to delay flower opening and inhibit floral organ growth, suggesting its role in regulating the timing of flowering and flower development (Liu *et al.*, 2009). Under stress conditions, such as drought, ABA levels increase, which can delay floral initiation and inhibit flowering altogether. This delay in flowering under stress is part of a survival strategy, where the plant postpones reproductive efforts until more favorable conditions are present (Koornneef *et al.*, 2002). Conversely, ABA has been shown to play a beneficial role in enhancing flower survival under stress. For instance, in some species, ABA signaling can increase flower longevity by delaying senescence, helping flowers persist longer under adverse environmental conditions (Sakamoto *et al.*, 2006). This ability to extend flower life under stress is important for plants that experience intermittent droughts or fluctuating temperatures, as it allows the plant to maximize reproductive opportunities when conditions improve.

ABA and Stress-Mediated Floral Male/Female Differentiation

One of the more fascinating aspects of ABA's role in floral responses is its involvement in regulating sex expression in dioecious plants. In species like hemp (Cannabis sativa), ABA has been shown to influence the differentiation of male and female flowers under stressful conditions. When plants are exposed to water stress, ABA can promote the development of female flowers, which are often more commercially valuable in these crops due to their higher content of secondary metabolites (Sharma *et al.*, 2020). This hormonal modulation of sex expression allows plants to adjust their reproductive strategies based on environmental stress. Abscisic acid is a critical regulator of stress-mediated floral responses in plants. Its ability to modulate flower initiation, development, and senescence under stress conditions makes it an essential player in reproductive success, particularly during environmental challenges. Although ABA's effects on floral responses are complex and often species-specific, its role in stress adaptation is undeniable. Understanding how ABA mediates these processes offers potential for improving crop productivity and resilience in the face of climate change and other environmental stressors.

Molecular and Genetic Regulation of Flowering

Flowering represents a crucial phase in the life cycle of angiosperms, marking the transition from vegetative growth to reproductive development. The timing and regulation of flowering are governed by a complex network of molecular and genetic pathways that integrate environmental cues and internal developmental signals. These pathways include photoperiod, vernalization, autonomous, gibberellin, and age pathways, all converging on key floral integrator genes such as FLOWERING LOCUS T (FT), SUPPRESSOR OF OVEREXPRESSION OF CONSTANS 1 (SOC1), and LEAFY (LFY) (Andrés and Coupland, 2012).

One of the central regulators of photoperiodic flowering is the CONSTANS (CO) gene, which promotes the expression of FT under long-day conditions in Arabidopsis. The FT protein acts as a mobile florigen that travels from the leaves to the shoot apical meristem (SAM), where it induces flowering by activating downstream genes such as SOC1 and APETALA1 (AP1) (Turck, Fornara and Coupland, 2008). This photoperiodic regulation ensures that flowering occurs during favorable seasonal conditions, maximizing reproductive success. Vernalization, the requirement for a prolonged period of cold to induce flowering, is another key regulatory mechanism, especially in temperate plants. This process is mediated by the repression of FLOWERING LOCUS C (FLC), a major floral repressor. Cold exposure leads to epigenetic silencing of FLC, thereby permitting the activation of floral promoters like FT and SOC1 (Amasino, 2010). Histone modifications, including H3K27me3, play a significant role in maintaining FLC silencing after vernalization, reflecting the importance of chromatin-level regulation in flowering control (He and Amasino, 2005).

The autonomous pathway functions independently of environmental cues and promotes flowering through the downregulation of FLC. Genes in this pathway, such as FCA, FPA, and FLD, regulate RNA processing and chromatin modification to suppress FLC expression (Simpson, 2004). This pathway ensures that flowering eventually occurs even under non-inductive environmental conditions, providing a developmental backup mechanism. Gibberellins (GAs) are also crucial in flowering regulation, particularly under non-inductive photoperiods. GAs promote flowering by upregulating LFY and SOC1 and by facilitating the degradation of DELLA proteins, which are repressors of GA signaling (Mutasa-Göttgens and Hedden, 2009). GA-deficient mutants, such as ga1-3 in Arabidopsis, exhibit late flowering, confirming the hormone's positive role in floral induction (Wilson *et al.*, 1992).

Furthermore, microRNAs (miRNAs) are emerging as significant regulators of flowering time. miR156 and miR172 function in the age pathway, with miR156 levels declining over time and allowing miR172 to accumulate. miR172 promotes flowering by repressing APETALA2-like genes that delay the floral transition (Wu *et al.*, 2009). The convergence of these pathways on central floral integrators enables plants to precisely time their reproductive phase. Advances in genomics and molecular biology continue to unravel the complexity of these regulatory networks, offering promising avenues for crop improvement and flowering time manipulation.

Application Strategies and Biotechnological Tools for enhancing Flower Induction and Quality

The optimization of flowering traits in horticultural and agricultural crops has been significantly enhanced through strategic application of plant growth regulators (PGRs) and the integration of advanced biotechnological tools. Efficient application strategies, combined with genetic and molecular innovations, contribute to the precise manipulation of flowering time, morphology, and quality, which are critical for yield improvement and market value. Application strategies involving PGRs such as auxins, gibberellins (GAs), cytokinins, ethylene, and abscisic acid (ABA) are tailored to species-specific and developmental-stage-specific needs. For example, the exogenous application of gibberellins has been effectively used to promote floral induction in long-day and biennial plants like Arabidopsis thaliana and sugar beet, where endogenous GA biosynthesis may be limiting (Mutasa-Göttgens and Hedden, 2009). Similarly, auxins are used in floriculture to promote pedicel elongation, reduce abscission, and enhance floral symmetry (Davies, 2010). Cytokinins, on the other hand, are applied to stimulate floral bud differentiation and improve flower size and longevity, particularly in ornamental crops such as orchids and lilies (Kulaeva *et al.*, 1991).

Precision in the timing, dosage, and mode of PGR application whether via foliar sprays, soil drenches, or injections ensures maximum efficacy while minimizing adverse effects such as floral deformation or delayed blooming (Rademacher, 2015). Furthermore, the synergistic or antagonistic interactions among hormones are also considered; for instance, balanced auxin-to-cytokinin ratios can optimize flower induction without excessive vegetative growth (Schaller *et al.*, 2015). In parallel, biotechnological tools are revolutionizing floral trait engineering. Marker-assisted selection (MAS) allows for the early detection of flowering-related genes, expediting breeding programs for desirable floral characteristics (Collard and Mackill, 2008). Genetic engineering and gene editing technologies such as CRISPR/Cas9 have facilitated targeted manipulation of flowering genes like FLOWERING LOCUS T (FT), CONSTANS (CO), and LEAFY (LFY) to control flowering time and architecture (Liu *et al.*, 2021). For example, CRISPR-mediated knockout of floral repressors like FLOWERING LOCUS C (FLC) has led to early-flowering phenotypes in Brassica species (Zhang *et al.*, 2018).

Transcriptomic and proteomic analyses further support the identification of regulatory networks involved in floral development. These tools help in elucidating gene expression dynamics under different hormonal treatments or environmental stresses, allowing for tailored intervention strategies (Song *et al.*, 2015). Synthetic biology approaches also offer promise in constructing custom regulatory circuits to fine-tune hormonal responses and flowering time. Moreover, nanotechnology-based delivery systems are being explored to enhance the precision and efficacy of

PGR application. Nanocarriers can facilitate slow release and targeted delivery of hormones, thereby reducing environmental impact and improving uptake efficiency (Kumar *et al*., 2021). Continued integration of molecular biology, plant physiology, and advanced breeding techniques will enable sustainable production of high-quality floral crops in diverse agroclimatic conditions.

Summary and Conclusion

Plant growth regulators (PGRs) play a pivotal role in governing the complex physiological, molecular, and developmental processes that culminate in flower induction and the enhancement of floral quality. Through intricate hormonal signaling networks, endogenous PGRs such as auxins, gibberellins, cytokinins, ethylene, and abscisic acid orchestrate the timing, architecture, and functionality of floral organs. The exogenous application of these hormones, when precisely managed, allows for targeted manipulation of flowering time, floral uniformity, flower size, color, and longevity traits that are essential for commercial horticulture, agriculture, and ornamental plant production. Each class of PGR exhibits distinct and often complementary roles. Auxins, through polar transport and the activation of specific transcription factors, regulate floral meristem formation and organ patterning. Gibberellins act as promoters of floral induction by degrading DELLA repressors and activating floral integrators such as LEAFY and SOC1, especially under non-inductive environmental conditions. Cytokinins enhance floral bud formation, floral longevity, and nutrient mobilization, while ethylene functions as a dual regulator promoting senescence in some species and controlling sex expression in others. Abscisic acid, often associated with stress responses, also modulates floral timing and viability under abiotic stress, linking developmental and environmental regulation.

The integration of biotechnological tools has further revolutionized our ability to understand and manipulate flowering. Techniques such as marker-assisted selection, transgenic approaches, CRISPR/Cas9 genome editing, transcriptomics, and proteomics enable the fine-tuning of genetic and hormonal pathways associated with floral traits. These innovations not only facilitate the development of improved plant varieties but also offer environmentally sustainable alternatives to conventional breeding and chemical-based methods. Application strategies must be species-specific and sensitive to developmental stage, hormone concentrations, and environmental conditions. Precision in PGR application is essential to avoid unintended effects such as delayed flowering, abnormal floral morphology, or reduced reproductive success. Advances in nano-formulations and slow-release systems provide novel avenues for improving hormone delivery and uptake efficiency, thereby increasing the reliability of desired floral outcomes while minimizing environmental impact. Looking forward, the challenge lies in harmonizing traditional agronomic practices with biotechnological and molecular innovations. A deeper understanding of hormone cross-talk, gene expression dynamics, and environmental interactions will be critical for devising resilient and adaptive strategies for floral enhancement. Future research should focus on developing smart PGR application systems that integrate sensor-based feedback, AI-guided modeling, and genomics to optimize flower induction across diverse climatic conditions and cropping systems.

In conclusion, PGRs are indispensable tools in the modulation of flowering and floral quality. Their synergistic application, guided by molecular insights and technological innovations, holds immense potential for advancing productivity, sustainability, and aesthetic value in plant-based industries. The convergence of plant physiology, molecular biology, and biotechnology will continue to shape the future of floral research and production, making it more efficient, predictable, and responsive to global agricultural demands.

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