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REVIEW ARTICLE

Optimizing flowering time in floriculture: Strategies for year-round production

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Abstract

The ornamental flower industry gradually shifts from conventional cultivation to extended cropping seasons and off-season production to meet market demands. Altering flowering time is highly desirable to ensure high-quality yields at targeted occasions such as festivities and weddings, thereby balancing trade by preventing market oversupply. Flower production is influenced by genetic makeup and a sequence of growth and developmental events. Recent studies highlight the role of specific genes in regulating flowering time and plant vigor, directly impacting yield quality. Key environmental factors such as vernalization, temperature and photoperiod are crucial in determining elite germplasm. While photoperiod control is well-studied in cereals and other crops, research in floriculture remains limited. Growth regulators assist in moderating plant growth, development and responses to biotic and abiotic stresses, either inducing flowering as a survival mechanism or delaying it under adverse conditions. These responses depend on stimulus intensity, plant developmental stage and cultivar characteristics. Understanding the regulation of flowering provides critical insights into optimizing harvest timing, minimizing market glut and enhancing produce value under varying environmental challenges.

Keywords

floral induction; genetic regulation; lighting; photoperiod; temperature

Introduction

Ornamental flowering plants come in various species and genotypes, categorized according to taxonomic criteria. These plants are cultivated primarily as a hobby due to their aesthetic appeal. However, with the advent of globalization and the rise of the market economy, flower cultivation has gradually evolved into a significant industry (1). In horticulture, the technique used to produce flowers outside their natural season is called forcing. It involves applying specific techniques to plants that have reached their stage of maturity, known as the ripeness-to-respond stage, to encourage flowering (2). The global floriculture industry is predominantly export-oriented, growing at an annual rate of 15%. The market is dominated by cut flowers, which make up as much as 60% of international trade, followed by potted plants, dried flowers and ornamental plant production (3). However, Europe dominates the global market for cut flowers and ornamental potted plants, contributing 31% of total sales, followed by China with 19% and the USA with 13%. Between 2006 and 2016, sales of cut flowers and ornamental plants in Europe increased by 7%, demonstrating gradual but consistent growth despite challenging global economic conditions (4). In 2017, the floral industry had a market size of approximately 74 billion USD, with significant contributions from Europe and Asia, accounting for 18% and 23% of the market (5).

In India floriculture sector experienced significant growth in 2023-2024, making a substantial contribution to domestic and global markets. The total production in the country reached 2,658.79 thousand tonnes for loose flowers and 876.52 thousand tonnes for cut flowers. This reflects India's strong position in the floriculture industry, meeting the rising demand for ornamental flowers. As the market expands, the sector continues to support livelihoods, enhance exports and strengthen the agricultural economy (6). Several ornamental plant species exhibit sustained global demand due to their significance in the floriculture industry, decorative applications and use in various ceremonial and commercial settings. Table 1 provides an overview of the most frequently utilized species, highlighting their primary uses and demand periods.

Farmers still rely on traditional methods, such as growing flowers seasonally, which leads to market gluts and price drops. Conversely, the same flowers could command much higher prices during the off-season (7). Considering the photosensitivity of these plants, we can influence and control the duration of their vegetative and reproductive phases, allowing for economical year-round production (8). A sustainable off-season flower market depends on profitability, requiring strategic investment in advanced cultivation techniques. Investors prefer cost-effective options like Exchange-Traded Funds (ETFs) due to lower fees and long-term gains. Adapting to market trends and managing costs ensures financial viability in floriculture (9). Technological shocks similarly boost private investment, but investment-specific shocks drive growth by temporarily lowering capital installation costs (Tobin's Q), while price markup shocks from inflation reduce overall investment indices (10).

Recent plant production advancements highlight nanoparticles and biochar's role in improving sustainability and efficiency. Nanoparticles, such as nano-encapsulated fertilizers and silver or gold nanoparticles, enhance nutrient delivery, plant growth and environmental sustainability. Biochar, known for its carbon sequestration and soil health benefits, may support off-season flowering in ornamental plants (11, 12). Adjusting photoperiod and day length and employing advanced techniques like genetic modification, hybridization, grafting and growth regulators have significantly improved production efficiency and commercial ornamental crop variety development (13). This article reviews the fundamental aspects of flower regulation in floriculture crops and explores how these processes can be strategically manipulated to benefit growers. With growing environmental challenges and economic pressures in agriculture, understanding and optimizing flowering time is essential for sustainable production. This helps support growers' economic viability by reducing market glut and increasing the value of produce under varying environmental conditions.

Mechanism of flower induction

Flowering is a complex process including biochemical, physiological and morphological changes (22). The initial stage of plant sexual reproduction is the shift of the apical meristem of a shoot from vegetative growth to reproductive. External cues, as well as endogenous signals, can trigger flowering (23). When leaves or meristems reach a state of maturity, they become capable of producing floral primordia through synthesizing specific hypothetical substances. These substances, known as vernalin, are made in response to appropriate temperature cues (24). However, the flowering hormone florigen is synthesized in the leaves and transported to the shoot apex to initiate flowering. Florigen production is triggered by suitable photoperiodic stimuli, ultimately leading to the onset of flowering (25). The activation of florigen in leaves plays a pivotal role in initiating the flowering process, serving as a critical regulatory mechanism, as illustrated in Fig. 1. Recent molecular genetics studies have identified the *FLOWERING LOCUS T* protein as the florigen in various plant species (26).

The various flower-promoting factors are detected by different parts of the plant. This indicates the outcome of the apical meristem, whether it remains vegetative or transitions to a reproductive state. It is determined by a network of long-distance signals originating from various parts of the plant (23). The flowering response is initiated when the apical meristem perceives the flowering stimulus and is exposed to sufficient inductive photoperiodic cycles, varying from one day to several

Table 1. Globally demanded ornamental plant species, their primary uses and demand periods

Species	Primary use	Demand period	References
Hybrid rose (*Rosa hybrida*)	Cut flowers, bouquets, weddings, perfume industry	February (Valentine's Day), May-June (Weddings)	(14)
Easter lily (*Lilium longiflorum*)	Religious ceremonies, cut flowers, garden plants	March-April (Easter), December	(15)
Florist chrysanthemum (*Chrysanthemum morifolium*)	Funeral arrangements, festivals, landscaping	November (All Hallows Eve, Funerals, Diwali)	(16)
Orchid (*Dendrobium nobile, Cymbidium* spp.*, Phalaenopsis amabilis, Vanda tricolor*)	Luxury floral arrangements, indoor decoration	December-February (Weddings, New Year)	(17)
Tulip (*Tulipa gesneriana*)	Landscaping, seasonal bouquets	March-May (Spring, Easter)	(18)
Gerbera (*Gerbera jamesonii)*	Bouquets, decorative flower arrangements	Year-round demand, highest in Weddings (May-July)	(19)
Snapdragon (*Antirrhinum majus*)	Cut flowers, landscaping	November-March (Winter floral demand)	(20)
Gladiolus (*Gladiolus grandiflorus*)	Cut flowers, events, garden display	August-October (Fall weddings, Festive decor)	(21)
Stock flower (*Matthiola incana)*	Wedding decor, cut flower arrangements	April-June (Wedding season, Spring demand)	(19)

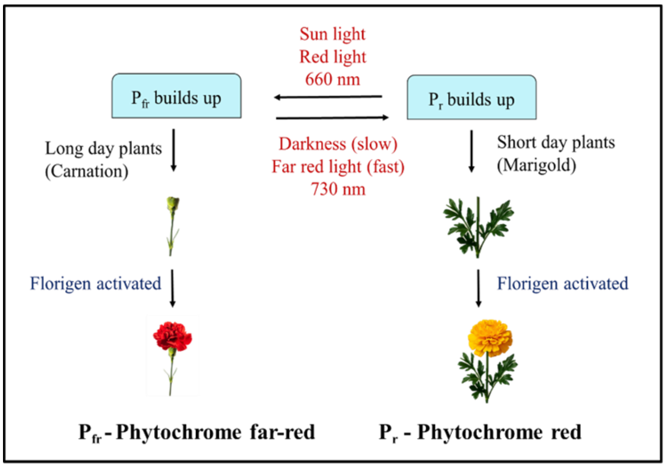

Fig. 1. Florigen activation in leaf tissues leads to the initiation of flowering.

weeks among species (27). Manipulating environmental conditions to induce flowering before the juvenile phase starts can result in low productivity (28). This is because plants need a specific period to accumulate sufficient mass for effective photosynthesis, which is crucial for the formation of flowers (28).

Genes involved in flowering

For most species, including the model plant *Arabidopsis thaliana*, a persistent transition from vegetative to reproductive growth relies on an external floral induction signal. Nearly 306 genes in *Arabidopsis* have been linked to time management and the *CTR (Calcitonin receptor)* gene was first isolated from *Arabidopsis* (29). FT belongs to the family of genes known as phosphatidyl ethanolamine-binding protein (PEBP) and 5 other genes have also been found to belong to this family in *Arabidopsis* (18). These members include *ARABIDOPSIS THALIANA CENTRORADIALIS (ATC), TERMINAL FLOWER 1 (TFL1), FT's TWIN SISTER (TSF), FT's BROTHER (BFT)* and *FT's MOTHER (MFT)*. While *TFL1, ATC* and *BFT* can function as floral repressors, *FT, TSF* and *MFT* are floral activators (29). An early blooming phenotype was similarly produced by overexpressing *LIFT* in *Lilium longiflorum*, which contributes to the development of meristem competence in response to stimulation associated with lily flowering (18). Specific genes play crucial roles in controlling flowering time by acting as activators or repressors. These genes regulate floral initiation, development and continuity across various ornamental plant species, as summarized in Table 2.

CsFTL1, *CsFTL2* and *CsFTL3* are *FT* genes from *Chrysanthemum seticuspe*. Among these, *CsFTL3* is the only gene to be a floral inducer, which is generated in the leaves in response to short-day stimulation (30). Under long-day conditions, *CsFTL1* is up-regulated, inhibiting or delaying flowering but having little floral function (31). To mitigate this effect, the scion of the heat-sensitive cultivar was grafted onto the rootstock of the heat-tolerant cultivar, leading to less heat impact on flowering at the shoot tip. In contrast, grafting the scion of the heat-tolerant cultivar onto the heat-sensitive stock resulted in heightened sensitivity to heat (16). Although *CsFTL2* is very weakly expressed in leaves, its expression in protoplasts suggests it has only minimal florigenic function (32). The gene product of *CsFTL3* may act as a graft-transmissible signal, or florigen, in the chrysanthemum. However, an antagonistic inhibitor may exist in the wild-type scion under non-inductive long-day conditions. This could be due to an insufficient transmission of graft-transmissible signals to the wild-type scion, preventing the complete development of the capitulum. This limited effect can be attributed to the sink-source relationship between the receptor shoot and the donor stock (31). Furthermore, *CsFTL3*-dependent graft-transmissible signals partially substituted for short-day stimuli to regulate flowering in chrysanthemums (30). Comparing transgenic plants to non-transformed plants, the transgenic plants showed earlier and more flowers (33). Six main pathways trigger the initiation of flowering: photoperiod pathway, ambient temperature pathway, vernalization pathway, age pathway, autonomous pathway and gibberellin pathway, illustrated in Fig. 2 (34).

Vernalization triggers flowering by suppressing *FLC* expression in response to prolonged cold exposure. Low temperatures activate antisense transcription at the *FLC* locus, leading to *COOLAIR* RNA production, which silences *FLC* transcription (35). Gibberellin (GA) acts as a key growth regulator in flowering, with *GIBBERELLIN 20 OXIDASE* (*GA20ox*) playing a crucial role in its biosynthesis by oxidizing multiple precursors. Before floral induction, bioactive GA4 levels rise at the meristem, promoting the transition to flowering (36). Higher temperatures (23 °C) accelerate flowering compared to lower temperatures (16 °C), largely influenced by the *SHORT VEGETATIVE PHASE* (*SVP*) gene. *SVP* inhibits *FT* transcription at low temperatures, whereas increased temperatures elevate *FT* mRNA levels, facilitating flowering. A mechanistic pathway of chemicals, light treatment and vernalization influences genetic expression. Regulatory signals activate floral genes, driving the transition to flowering illustrated in Fig. 3.

Table 2. Role of specific genes in regulating flowering time across various ornamental plant species.

Species	Gene	Early/ Late flowering	References
Chrysanthemum (*C. morifolium)*	*CmFL, CmAFL1 and CmSOC1* *CsFTL2* *CsFTL3* overexpression *CmBBX8* overexpression	Early Early Early - under LD Early - under LD and SD	(30, 37-39)
Chrysanthemum*(C. indicum)*	*CiFTL1*	Regulate the time of the flowering	(40)
Transgenic chrysanthemum	*AP1* gene overexpression	Early	(41)
Rose (*R. indica*)	*RoKSN* Shoot apex *RoFT*	Delay Early	(42) (43)
Rose (*R. hybrid)*	*TFL1* orthologous	Continuous	(44)
Lilium (*L. longiforum*)	*LIFT* overexpression	Early	(18)
Tulip (*T. gesneriana*)	*TgFT2* and *TgFT3* over expression	Early	(18)
Gerbera (*G. hybrida*)	*GSQUA2* transformation	Early	(45)
Gloxinia (*Sinningia sp.)*	*LFY* over expression	Early	(46)
Gloxinia (*S. speciosa*)	*miRNA159* over expression *miRNA159* suppression	Late Early	(47)

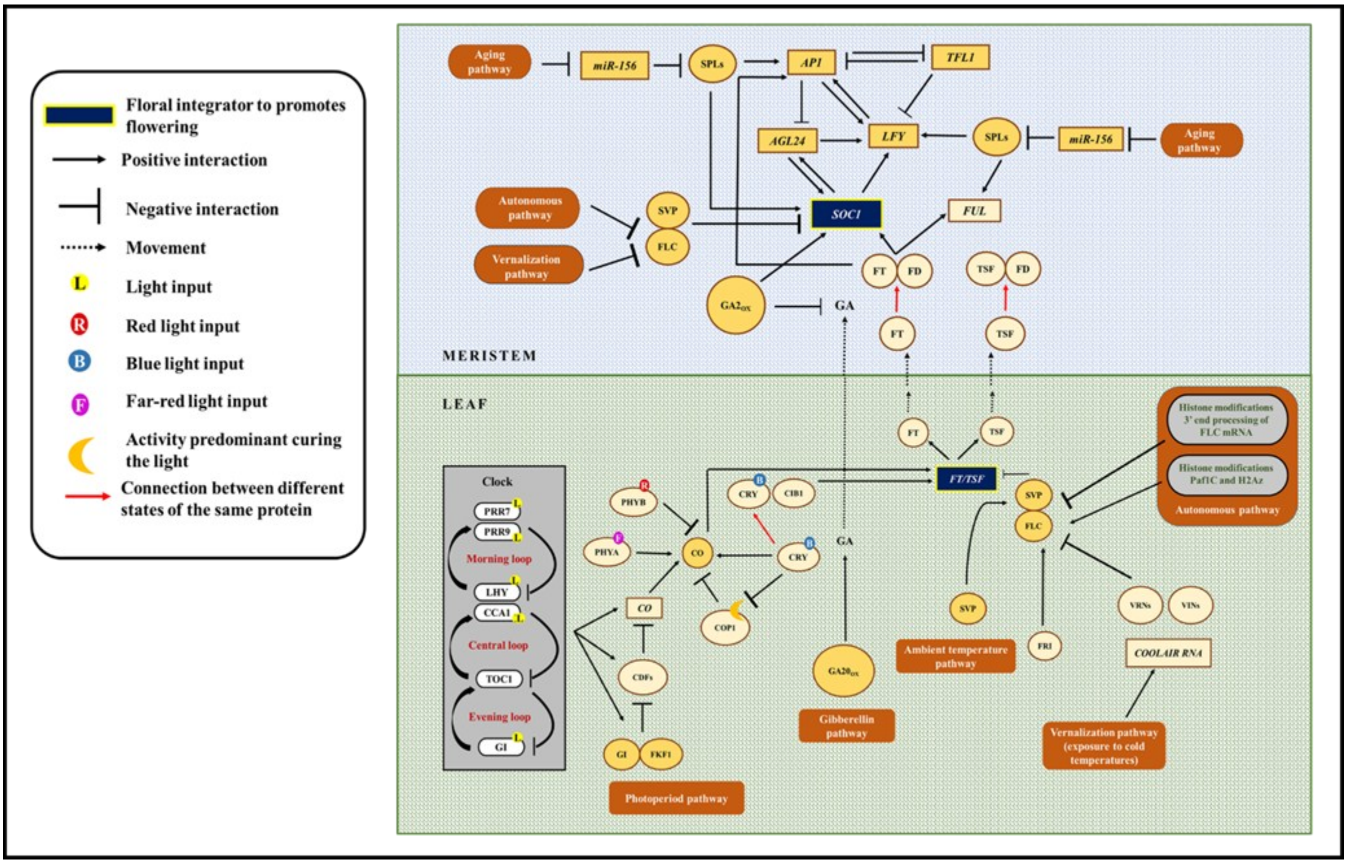

Fig. 2. Genetic pathways regulating flowering in *Arabidopsis* involve complex networks that integrate environmental signals and internal cues to orchestrate floral initiation and development.

Note: SPL - *SQUAMOSA PROMOTER BINDING* LIKE, AP1 - *APETALA1*, TFL1 - *TERMINAL FLOWER 1*, AGL24 - *AGAMOUS-LIKE 24*, LFY - *LEAFY*, FUL – *FRUITFULL*, SVP – *SHORT VEGETATIVE PHASE*, FLC - *FLOWERING LOCUS C*, FD - *FLOWERING LOCUS D*, TSF - *TWIN SISTER OF FT*, GA - GIBBERELLIN, VRN – VERNALIZATION, VIN - VERNALIZATION INSENSITIVE, CRY – CRYPTOCHROME, CIB1 - CIRCADIAN INTERVAL-BINDING 1, CO - CONSTANS, COP1 - CONSTITUTIVE PHOTOMORPHOGENIC 1, PHYA - PHYTOCHROME A, PHYB – PHYTOCHROME B, CDF - CYCLING DOF FACTOR, GI – GIGANTEA, FKF1 - FLAVIN-BINDING KELCH REPEAT F-BOX 1, GA2OX - GA 2-OXIDASE, GA20OX - GIBBERELLIN 20 OXIDASE, TOC1 - TIMING OF CAB 1 , CCA1 - CIRCADIAN CLOCK ASSOCIATED 1, LHY - LATE ELONGATED HYPOCOTYL

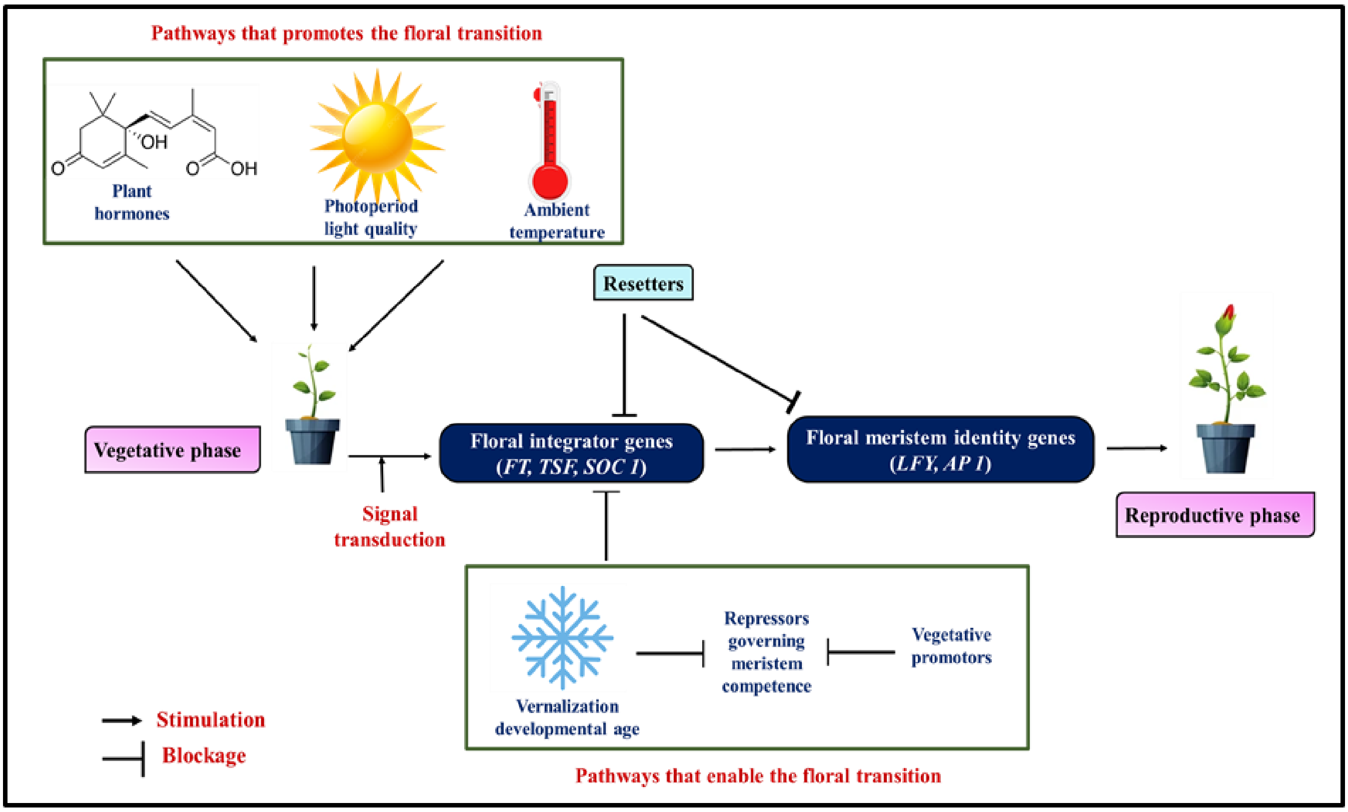

Fig. 3. Mechanistic pathway of chemicals, light and vernalization affecting floral genes.

Note: CO - *CONSTANS*, FLC - *FLOWERING LOCUS C*, FT - *FLOWERING LOCUS* T, TSF - *TWIN SISTER OF FT*, SOC 1- *SUPPRESSOR OF OVEREXPRESSION OF CONSTANS 1*, LFY - *LEAFY*, AP1 - *APETALA1*

Flowering behavior of some important ornamental crops

Flowering can occur year-round with or without seasonal influence in certain flower crops, such as roses, marigolds and heliconias. In these plants, flowering can occur consistently regardless of the time of year (24). Regulating flower production not only ensures a year-round supply of fresh produce but also reduces market gluts through controlled supply, prevents spoilage or wastage, increases growers' income with better off-season returns and provides year-round employment (20). Understanding flower regulation can help optimize harvest timing, prevent spoilage from overproduction at specific periods, reduce market oversupply, ensure year-round employment and maintain a trade balance (48).

Factors inducing flowering in ornamentals

The flowering of ornamental crops is influenced by certain factors such as growing in a greenhouse, changes to temperature or light that might take the place of the flowering input, which is dependent on a particular circumstance, i.e., photoperiod, growth hormones, modification of plant biomass are explained in Fig. 4. The plant's genetic makeup, growing environment and cultivation circumstances can all cause flowering. To control the timing of flowering, various greenhouse floriculture techniques have been created, utilizing inherited, biological and technical methods (27). By understanding crop physiology and flowering behavior in different environmental conditions, we can manipulate plants to flower at the planned schedule (20). Factors affecting flowering in ornamental crops, as shown in Fig. 5.

Greenhouse Conditions

Greenhouses integrate automated control systems and sensors monitor and regulate key inputs such as temperature, humidity, CO_2, pH, electrical conductivity and shading also serve as a crucial facility for mitigating both biotic and abiotic stresses on crops, allowing for year-round cultivation even during off-season periods (20). According to Proietti, Scariot elements of the plant–environment binomial may be used in greenhouse floriculture production scheduling strategies (27). As a result, operations can be divided into 3 groups based on their actions: a) Straight onto the crop, b) On the development habitat, c) Using technology that incorporates the entire growing system in the production process e.g., hydroponics Typically, this strategy is used to schedule flower crops like

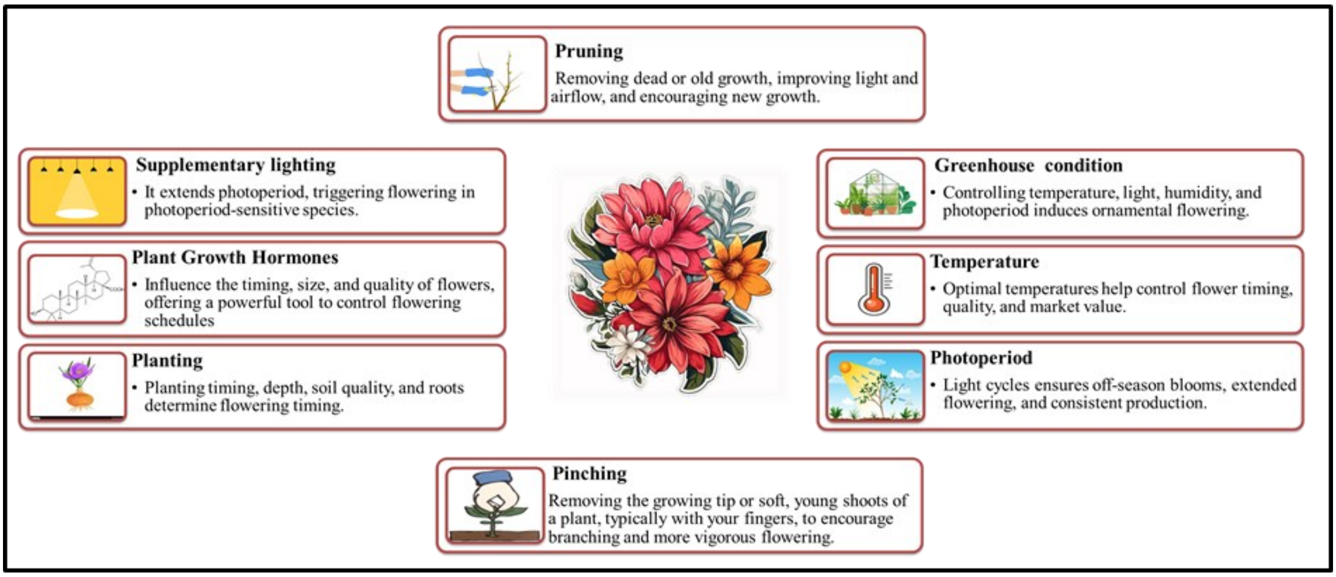

Fig. 4. Factors for inducing flowering in ornamentals.

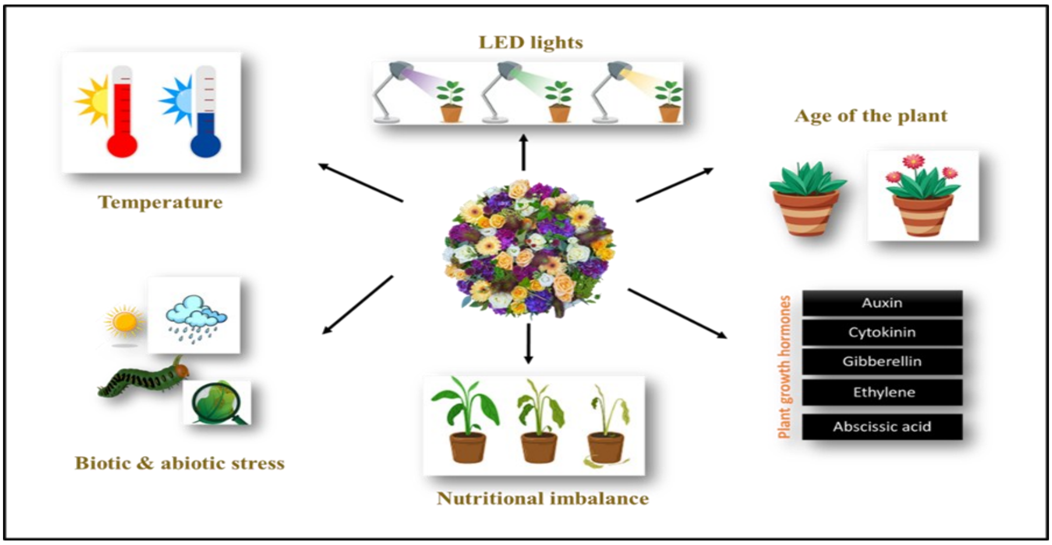

Fig. 5. Factors affecting flowering in ornamental crops.

Note: Environmental factors (Light, Temperature), Genetic factors (Plant species, Variety), Cultural practices (Fertilization, Plant growth hormones), Physiological factors (Plant age, Nutrient availability) and Biotic & Abiotic stresses (Pests, Diseases, Drought).

snapdragon (*Antirrhinum majus*), Lisianthus (*Eustoma russellianum*) and stock (*Matthiola incana*) which are herbaceous plant species, typically exhibiting biennial or perennial growth habits, are managed as annual crops for cut flower production.

Daytime temperatures between 15 °C and 40 °C are essential for efficient photosynthesis in greenhouses. However, these temperatures are not necessary at night, as plants are not actively growing during that time (49). To optimize crop growth and align the control system with flowering schedules, it's essential to understand the physiological flowering needs of each crop, enabling tailored scheduling and regulation. The use of sensor technology equipped with automation software tools in greenhouses can revolutionize flower production during the off-season (20). The length of developmental phases in a plant species is capable of differs based on its genotype and environmental conditions (27). Snapdragon, lisianthus and stock cultivars are selected based on their responses to various climatic conditions. Achieving non-seasonal cut flower production is possible by alternating various genotypes in cold or heated greenhouses (50). For instance, Snapdragon cut-flower production is achievable year-round by selecting cultivars suited to seasonal conditions, ranging from low-light and cooler nights at 7 - 10 °C to high-light and warmer nights above 16 °C. For ornamental crops, we can regulate flowering by adjusting the greenhouse temperature, which allows us to optimize the flowering in temperature-sensitive crops (20).

Temperature

Flowering time is regulated by ambient temperature, which adjusts the phenological development rate (51). Temperature is the most commonly regulated factor in greenhouses, managed either directly through heating and cooling or indirectly through ventilation and humidity control (51). By controlling temperature by both increasing and decreasing it, especially in Mediterranean climates, i.e., due to elevated levels reached, plants biological clocks can be adjusted by influencing thermal time and also regulate numerous endogenous physical and chemical factors affecting plant growth and maturation (52). Physiological and developmental reactions such as leaf unfolding, flower commencement and flower development are caused by changes within the existing temperature level (53).

According to Proietti, Scariot rate of enzymatic processes and plant growth increases with rising temperatures, shortening each growth phase (27). This effect occurs within specific limits:

a) The base temperature (T_{base}), below which growth ceases, but the plant stays alive

b) The optimal temperature (T_{opt}), where growth is fastest and balanced

c) The critical temperature (T_{crit}) beyond which growth halts.

In chrysanthemums, cold temperatures and the application of gibberellic acid are critical for inducing continuous flowering (54). Combining vernalization with a plant growth retardant, such as Cultar™ or Paclobutrazol, has been shown to increase flower production in chrysanthemum cv significantly White Star (55). During the vegetative stage of chrysanthemums, an average temperature of 23.17 °C with 5.62 h of sunshine and during the flowering stage, 35.10 °C with 4.20 h of sunshine, enhance flowering parameters (56). In Kalanchoe, flowering onset is observed at a nocturnal temperature of 18 °C (57). For tuberose, storing bulbs for 7 weeks at 27 °C results in early flowering, whereas storing them for 6 weeks at 12 °C delays flowering (58). In Lilium, bulb treatment at 2.5 - 7.5 °C promotes flowering (59), while day/night temperatures of 36 °C/28 °C in roses encourage early flowering (60). However, in chrysanthemums, heating at 30 °C between midnight and early morning delays flowering by over 25 days (16). *Dendrobium nobile* requires a temperature from 13 to 15 °C to trigger flowering in D. Sea Mary 'Snow King.' If the temperature goes beyond 15 °C affects flower production (61). The impact of temperature on ornamental plants is listed in Table 3.

Photoperiod

Photoperiod refers to the duration of light and dark periods that plants detect within a 24-h cycle as well as regulate various developmental responses in plants, including flowering (66). Plant species can be divided into 3 categories based on their photoperiodic requirements: day-neutral plants (NDP), which flower regardless of the length of the day; short-day plants (SDP), which flower at a short day period or a long night and long-day plants (LDP), species that require extended daylight to initiate flowering (22). Fig. 6 depicts the blooming patterns of short and long-day plants, emphasizing each plant type's photoperiodic influence on flowering.

Short Day Plant (SDP)

In SDP, the day length is shorter than a critical value; plants need a short daylight period of 8 - 10 h followed by an uninterrupted period of darkness of 14 - 16 h to induce flowering (67). Night interruption during short days enhances flowering kinetics in LDP, resulting in accelerated production. Conversely, night interruption (NI) during long-day seasons can hinder the flowering of SDP (68). Applying NI treatment during their reproductive stage induces early flowering of *Doritaenopsis* orchids (69). *Ageratum houstonianum, Dianthus chinensis* and *Petunia hybrid* cv. 'Easy Wave Burgundy Star,' *A. majus* and Verbena hybrid flowered 12, 4, 24, 18 and 18 - 22 days earlier under NI lighting compared to a 9-h SD

Table 3. Influence of temperature variations on flowering in ornamental plant species

Species	Optimal temperature	Early/Late Flowering	References
Orchid (*Phalaenopsis)*	29 °C/17 – 23 °C Day/Night	Late	(31)
Chrysanthemum (*Chrysanthemum morifolium)*	Greater than 20 °C Heating at 30 °C from midnight until dawn	Late 25 days late	(16)
Tulip (*Tulipa* sp.)	7 °C for 70 days	Early	(31)
Narcissus (*Narcissus tazetta)*	Greater than 25 °C	Early	(62)
Petunia (*P. hybrida)*	26 °C	Early	(63)
Hydrangea (*Hydrangea macrophylla)*	17 °C	Early	(64)
Cyclamen (*Cyclamen persicum)*	20 °C	Early	(65)
Asiatic hybrid Oriental hybrids	0 °C – 7.5 °C 0 °C – 7.5 °C	Early	(59)

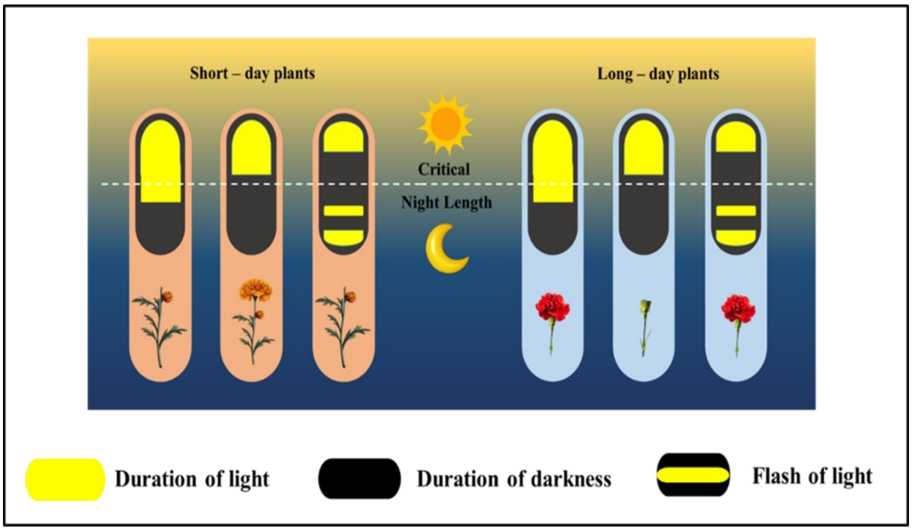

Fig. 6. Flowering responses of short-day and long-day plants to critical night length.

Note: Short-day plants bloom when the duration of uninterrupted darkness exceeds a critical night length. Long-day plants bloom when darkness is shorter than a critical night length.

photoperiod (70). A short day with a 4-h NI treatment and an 8-h short day promoted early flowering in *Chrysanthemum seticuspe* (30). In contrast, an 8-h short day with a 4-h NI treatment and a 16-h long day induced late flowering (59). In poinsettia, high temperature influences the flowering, keeping bracts green, i.e., failing to develop red coloration. Specialized lighting delayed marigold blooming by 2 weeks and changed plant growth, with SD plants growing 31—37% shorter and producing 6—7 extra leaves (71). In kalanchoe, 9 - 12 h of photoperiod promotes 100% flowering; more than 12 h of decline flowering, however, augmented the number of nodes below the terminal inflorescence (72). In *C. morifolium* 12 h long day promotes early flowering (21).

Long Day Plant (LDP)

In LDP, blooming is stimulated when the duration of darkness is shorter than a specific critical period (73). In temperate regions where natural photoperiods are short, artificial long-day conditions can boost flowering intensity (74). LDP cultivated in short-day conditions showed an inverse relationship between night break and flowering time, where flowering could be accelerated. Under a 9-h short day, the petunia "Easy Wave Coral Reef" stayed in the vegetative stage but responded with a qualitative long-day phase (75). Chrysanthemum (*C. morifolium)*, plants exposed to 9-h and 10.5-h photoperiods required fewer days to flower, taking 121 and 129 days respectively, while unexposed plants took significantly longer, requiring 228 days to flower (71). In Lilium (*L. longiflorum)*, Low light levels combined with long-day treatment were found to reduce the number of flower buds and increase plant height (59). As the photoperiod in Tecoma (*Tecoma stans)* increased from 12 - 16 h, the number of days until the first open flower declined by 11 days (76).

Supplementary lighting (SL)

Red and blue light is absorbed by plants and used to regulate photosynthesis, leaf growth and flowering (77). Despite being a prominent floricultural crop due to its light-sensitive flowering habit, little is known about the molecular mechanisms underlying chrysanthemum photoperiodic flowering (78). By promoting photosynthesis, light assists plants in producing carbon-based compounds and acts as an environmental cue (79). The night interruption (NI) with low-level light-emitting devices LEDs will encourage plant growth and have a moderate impact on net photosynthesis (31). At the end of the seedling stage, implementing FR radiation supplemental lighting SL with LEDs for 14 days helps LDPs bloom earlier because Blue + Red + Far-red supplementary lighting shortened the time until the first visible sign and flower (7-28 days) by 3 and 8 days for calibrachoa *(Calibrachoa hybrida)* and snapdragon (*A. majus)*, correspondingly (80).

In chrysanthemums, blue-extended light with long days in growth chambers promoted floral initiation and capitulum development. Similarly, red-extended light allowed flower initiation but hindered capitulum development (81). Prolonged exposure to blue light inhibited chrysanthemum flowering, whereas short exposure to blue light was less effective in delaying flowering than white or red light (82). Artificial lights, sometimes known as day-length extensions, are used by chrysanthemum farmers to satisfy the year-round demand for marketable flowers (25). All 3 types of light treatments-white, blue and red shortened the time for sprouting and flowering in *Tulipa gesneriana* L., while blue light had the most significant effect, 10% and 11% (83). Warm white (WW) LEDs and cool white (CW) LEDs produce year-round flowering of Phalaenopsis under greenhouse conditions. Both types of LEDs enhanced inflorescences' proliferation and florets' number and size. However, the WW-LED had a more significant impact than the CW-LED (84). The incandescent lights NI R: FR = 0.59 and LEDs with R: FRs of 0.66 - 2.38 and 0.28 - 1.07 showed the most significant increase in flowering of LD plants, such as petunia and snapdragon, however LEDs with R: FRs of 0.66 - 2.38 and 0.28 - 1.07 inhibited flowering in SD plant such as marigold (85). The growth of *A. majus* and *P. hybrida* was accelerated by employing a 16-h photoperiod, red, far-red light lamps and a high DLI (86). Higher quantities of UV radiation degrade quality and production factors, but moderate amounts of UV can stimulate certain species (87). Similarly, UV-C 250-280 nm irradiation *Freesia hybrida* corms produced early flowering in 10.4 days and elevated lateral growth and flower count up to 22 and 30%, respectively, in comparison to non-treated controls (88).

Plant Growth Hormones

Certain plant hormones, including gibberellins, abscisic acid, auxins and ethylene, play significant roles in influencing flowering, as explained in Fig. 7 (89). Exogenous gibberellins can replace photoperiodic signals in certain long-day plants as well as regulate plant growth and development processes, such as seed germination, stem elongation and the change from vegetative to flowering growth (90). Table 4 overviews key chemicals, their commercial names, application methods and effects on flowering and postharvest longevity. The use of GAs induced early flowering as well as enhanced the quantity of flowers in china aster and gladiolus (91, 92). In marigolds (*Tagetes erecta*), GA3 resulted in early flower bud initiation, the opening of the first flower and an extended flowering period (93). In jasmine (*Jasminum sambac*), foliar spray of 100 ppm gibberellic acid after pruning at 60 cm above the ground (94). Applying gibberellic acid (GA3) to the foliage during cultivation promotes flowering and enhances floral development in biennials such as calendula and carnation, even under short-day conditions and without cold exposure (90).

Auxin is also crucial for the beginning and determination of floral organs (95). IBA at 400 ppm was used to determine the minimal number of days required for flower bud initiation in *Dianthus caryophyllus* (96). When carnations were treated with NAA at 500 mg L^{-1}, the time to rooting, early rooting, high rooting rate and the number of roots per cutting significantly decreased (97). Lotus plants exhibited longer flowering times, thicker leaves and longer scapes following the external application of 28-epihomobrassinolide (98). Solely ethylene facilitates flower formation (99). In *J. sambac*, plant growth retardants such as CCC at 1000 and 2000 ppm and paclobutrazol at 300 ppm, applied as a soil drench and pruning, resulted in the highest flower yield (100). Other species are explained in Table 5.

Planting

The timing of planting and flowering is crucial to meeting flower demand, ensuring quality blooms year-round by adjusting the climatic conditions. Variations in planting time play a vital role in optimizing ornamental plant production systems (112). The selection of variety, cultivar, or hybrid, along with the planting date, affects flowering timing and winter production, ultimately maximizing the economic worth of the plants (27). The selection of propagation material is crucial for geophytes, as the size and quality of the material directly influence the success of propagation, growth and overall plant development (113). In bulbous crops, planting typically starts in spring to maximize spike production (114).

Table 4. Chemicals and hormones used for flower induction and shelf-life extension in ornamental plants

Chemical/Hormone	Commercial/ Trade Name	Method of Application	Effect	References
Gibberellic Acid (GA_3)	ProGibb, GibbGro	Foliar spray, drenching, injection	Stimulates flowering enhances stem elongation, promotes uniform blooming in cut flowers	(101)
Benzyl Adenine (BA)	MaxCel, Configure	Foliar spray, dipping	Delays senescence, enhances bud opening and branching	(102)
Cytokinins (Kinetin, Zeatin)	Cytokin, ZeaMax	Foliar spray, injection	Stimulates flower bud differentiation enhances floral longevity	(99)
Silver Thiosulfate (STS)	Chrysal AVB, Floralife STS	Stem absorption	It inhibits ethylene production and prevents premature petal wilting and abscission in carnations, orchids and lilies.	(103)
1-Methylcyclopropene (1-MCP)	EthylBloc, SmartFresh	Fumigation, vapor treatment	Extends vase life of ethylene-sensitive flowers	(104)
Salicylic Acid (SA)	Aspirin	Foliar spray, vase solution	It enhances stress tolerance, delays petal senescence and increases water uptake in cut flowers.	(99)
Abscisic Acid (12)	ProTone, Dormex	Foliar spray, drenching	Regulates flowering cycles, improves drought tolerance in potted ornamental plants	(103)
Ethephon (ET)	Florel, Ethrel	Foliar spray, drenching	Induces flowering, promotes uniform flowering	(21)

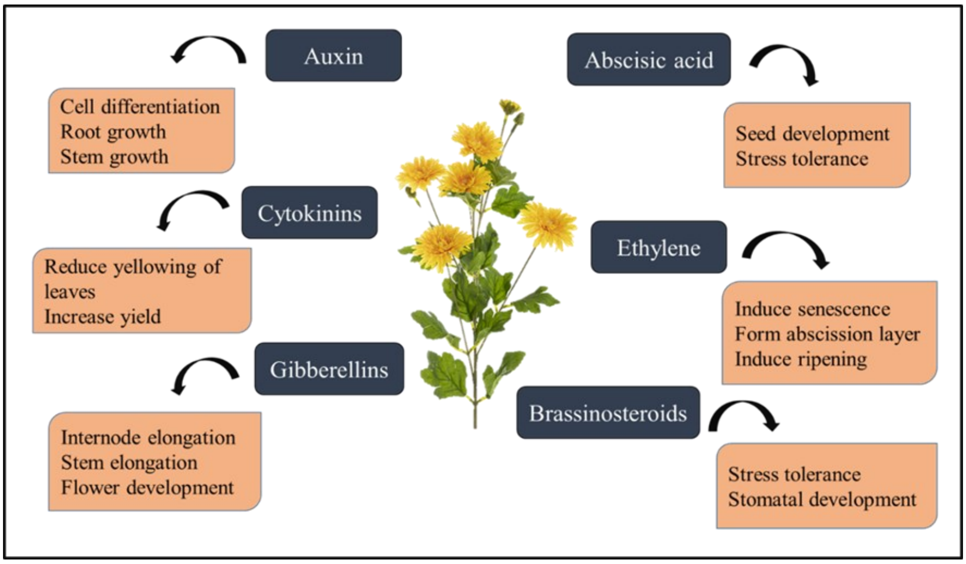

Fig. 7. Role of plant growth regulators in modulating flowering by influencing hormonal levels, bud development and overall plant growth.

Table 5. Effect of plant growth regulators on flowering control in ornamental plants

Species	Active ingredient & Concentration	Early/Late Flowering	References
Gerbera (*G. jamesonii*)	GA3 50 ppm	Early	(105)
Chrysanthemum (*Chrysanthemum* spp.)	GA3 50 ppm	Early	(106)
Tuberose (*Agave amica*)	GA3 100 ppm GA3 150 ppm	Early	(107)
Gladiolus (*G. grandiforus*)	GA3 300 ppm GA + BAP 100 mg L^{-1}	Early Not influenced	(21)
African marigold (*T. erecta*)	GA3 100 ppm GA3 150 ppm GA3 200 ppm GA3 300 ppm GA3 400 ppm	Early	(31)
Carnation (*D. caryophyllus*)	GA3 150 ppm + IAA 300 ppm	Early	(108)
China aster (*Callistephus chinensis*)	GA3 150 ppm CCC 1500 ppm	Early	(91) (109)
Gaillardia (*Gaillardia pulchella*)	GA3 200 ppm	Early	(104)
Kalanchoe (*Kalanchoe* spp.)	GA3 100 mg L^{-1}	Early	(110)
Calendula (*Calendula offcinalis*)	GA3 100 ppm	Early	(111)

Note: GA gibberellic acid, CCC cycocel IAA Indole-3-Acetic Acid, BAP 6-benzyl aminopurine

July planting led to gladiolus flowering by September, with varieties like Punjab Glance and Punjab Lemon Delight thriving under longer days and more heat, producing quality spikes (115). Additionally, planting corms of gladiolus cultivar 'Solan Mangla' on July 28 enhanced flowering (116). In Chrysanthemum, early planting resulted in the most prolonged flowering period of 40 days and the highest flower count. Planting on either April 6th or April 21st accelerated flowering and extended the blooming duration (117). In Gladiolus, early flower induction is achievable with larger corms, while more minor corms experience delayed flowering until mid-summer or even autumn (27). Spacing of 30 × 30 cm has been found to maximize the percentage of florets opening on tuberose spikes (118).

Plant biomass manipulation

Pruning: It helps be an effective technique for inducing the off-season flowering of many ornamental plants. It is a crucial exercise for controlling growth. This approach broadens the C:N ratio, which stimulates flowering (119). The exchange of carbon and nitrogen between shoots and roots via the xylem and phloem is crucial for plant metabolism. Nitrogen supports carbon metabolism through protein synthesis, while carbon compounds aid nitrogen uptake, nitrate reduction, nitrogen fixation and amino acid metabolism by providing carbon skeletons, energy and reducing agents. C and N act as signaling molecules, regulating nutrient absorption, assimilation and photosynthesis. Their influence on gene expression, enzymatic activities and signal transduction pathways ultimately affects plant growth and crop yield (120). The primary objective of pruning in flowering ornamentals is to stimulate flowering shoots through the creation or enhancement of metabolic sinks (121). Jasmine, the height at which a plant is pruned is determined by its vigor a lower cut results in fewer buds and fewer but stronger stems, whereas a higher cut retains more buds, producing a larger quantity of stems but with diminished quality traits, such as stem length, leaf count and blossom size (27). Regular pruning of bougainvillea caused early flowers by inducing cytokinins to produce buds (122). In *J. sambac,* plant density and frequent pruning significantly influence the bloom, with three plants per pit as well as biannual pruning boosting new shoots and high-quality flower buds across all seasons (123). However, in late September, combined with soil drenching of 300 ppm paclobutrazol, 0.5% thiourea and two foliar sprays at 30 and 60 days, the application of cycocel at 1000 ppm enhanced flower quality parameters (124-127). Pruning in October and applying 1000 ppm Cycocel 15 days later enhanced growth and flower production (128). In *Jasminum auriculatum*, changes in October weather conditions indicate that pruning should be carried out during the final week of October, with cuts made 30 cm above ground level, maximizing yield (129). When pruned towards the end of December, rose plants displayed a higher number of flowers, a larger diameter and weight of flowers and a shorter time to first bud emergence. When pruned in the last week of December, plants exhibited more abundant blooms, along with larger flower diameters and increased flower weight (121). It serves commercial purposes to manage fluctuations in rising demand for roses outside traditional seasons (130). In *Rosa damascena,* pruning on January 15th led to the shortest duration for reaching flowering stages, with only 54 days from leaf to flower bud and 12 days from floral bud formation to anthesis (131).

Pinching: It involves manually removing new growth from a plant to encourage branching and the development of more shoots. This technique results in shorter, more compact plants with increased blooms by promoting bushier growth and a more significant number of flowers (132). Pinching not only enhances the plant's aesthetic appeal but also promotes a more significant number of viable and aesthetically pleasing flowers (133). Three pinching methods include single pinching at the 5-node phase for early crops, pinch-and-a-half for main stem and shoots and double pinching, repeated when shoots reach 6 - 8 cm height (134). Double pinching in African marigold cv. Gainda Pusa Narangi improved flower count (63) and blossom size (5.05 cm), though its full effects on marigold flower production remain unexplored (31). Further, it lengthens the time required to reach 50% flowering because it takes longer for newly growing branches to get the reproductive phase (135). In Zinnia cv. Sun gold, double pinching results in many flowering days (136). In lisianthus, double pinching led to the most prolonged duration for the first flower initiation, while unpinched plants required the least time (137). In contrast, crape jasmine (*Tabernaemontana divaricate)* exhibited a late floral induction period in pinched plants compared to unpinched plants (138). Similar outcomes were shown in China aster, where pinched plants experienced delays in the days for floral bud the process of emergence bud opening, first flowering and 50% flowering (139).

Conclusion

Fresh flowers and foliage plants are highly sought for various applications, including essential oils, cosmetics, aromatherapy, dried flowers, potpourris, natural dyes and medicinal uses. This review provides a comprehensive analysis of flower regulation mechanisms, focusing on environmental influences and artificial (genetic) manipulation. Developing efficient cultivation strategies is crucial to maximizing benefits with the increasing adoption of protected cultivation for flower crops. Extensive research has explored the effects of temperature, photoperiod, nutrition and growth regulators on flowering across various species. Flowering is a complex process influenced by multiple environmental factors, including light, temperature, plant nutrition and micronutrient availability. Photoperiod control, mainly through night interruption lighting has been shown to either promote or delay flowering based on light duration, intensity and timing. Growth regulators play a key role in modifying plant morphology and physiology, significantly enhancing growth, yield and flower quality. As climatic conditions change, new classes of plant growth regulators present opportunities for optimizing ornamental plant production when integrated with fertility and irrigation management. A deeper understanding and precise interpretation of these regulatory factors enable better crop scheduling and flowering cycle adjustments. However, further research is needed to develop standardized methodologies and explore the intricate relationships between flowering cycles and influencing factors. Only a limited number of systematic studies exist on floriculture crops, highlighting the need for extensive, integrated research to derive conclusive insights into optimizing flowering regulation.

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Authors' contributions

BJ and CR write the original draft and conceptualization. KRR carried out revision of the draft, including tables and figures and proofreading. TS and PCNM performed revision, formatting and supervision. All authors read and approved the final paper.

Compliance with ethical standards

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