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Flowering in Vegetable Crops: Mechanisms, Regulation and Agronomic Implications

Akshita Sharma[1*], Shreya[1], Dikshika Thakur[1]
[1]M.Sc. Student, Department of Vegetable Science, COHF, Neri, Dr. YSPUHF, Nauni, Solan, Himachal Pradesh, India
[*1]Corresponding author: axusharma2004@gmail.com

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Abstract

Flowering represents one of the most critical developmental transitions in the life cycle of vegetable crops, marking the shift from vegetative to reproductive growth. This transition is governed by a complex interplay of environmental signals (photoperiod, temperature, light intensity and water availability), physiological mediators (phytohormones) and an intricate genetic regulatory network involving circadian clock genes and floral pathway integrators. Understanding these mechanisms is pivotal for crop improvement, manipulation of flowering time and adaptation to changing climatic conditions. This review synthesizes current knowledge on the environmental, physiological and genetic control of flowering in vegetable crops, with particular emphasis on photoperiodism, vernalisation, phytohormone action and the molecular genetics of floral induction.

1. Introduction

Flowering is a pivotal developmental transition in the life cycle of plants, marking the onset of reproductive growth. During this phase, the plant shifts from accumulating biomass in vegetative structures such as leaves, roots and stems to differentiating vegetative meristems into floral meristems, culminating in the formation of functional floral organs. (Das et al., 2025; Tan et al., 2024).

The vegetative shoot apical meristem (SAM) undergoes transformation into a reproductive floral meristem, a process involving synchronized morphological changes. Three morphological stages are recognized: floral induction, floral initiation and floral differentiation. A combination of physiological, hormonal and genetic factors regulates these stages. (Singh et al., 2026).

In vegetable crops, timely flowering is economically critical. Premature bolting in leafy and root vegetables can render produce unmarketable, while delayed or incomplete flowering in fruiting vegetables directly reduces yield and seed production. Understanding and manipulating flowering thus underpins the entire chain of vegetable production, from variety development to precision crop management.

A complex interplay between exogenous environmental factors such as photoperiod, temperature, water availability and endogenous signals including hormones and genetic factors controls flowering. (Singh et al., 2026).

2. Developmental Stages of Flowering

2.1 Floral Induction

Floral induction represents a critical transition during which plants perceive environmental and endogenous signals such as photoperiod, temperature, hormonal balance and developmental age. Although no visible structural changes occur at this stage, significant physiological and molecular events take place, including the activation of flowering genes, redistribution of assimilates and changes in hormone concentrations that prepare the plant for flowering. (Singh et al., 2026).

2.2 Floral Initiation

Following floral induction, floral initiation begins with distinct morphological changes in the shoot apical meristem (SAM). The vegetative meristem enlarges, flattens and differentiates into a floral meristem, marking the onset of flower development. In vegetable crops such as tomato, onion, cabbage and cucurbits, successful initiation is essential for timely fruit set, seed production and yield.

2.3 Flower Bud Differentiation and Development

Floral differentiation encompasses the development and precise arrangement of floral organs, including sepals, petals, stamens and the pistil. Fruiting potential, fertility and flower structure are all determined at this stage. Hormonal gradients and floral homeotic genes control the precise sequence of morphological differentiation. Any disturbance during this phase, such as a hormonal imbalance or nutritional shortage, may lead to inadequate ovary growth, deformed flowers, or decreased pollen viability. (Singh et al., 2026).

3. Environmental Factors Affecting Flowering

Table 1. Summary of environmental, physiological and genetic factors influencing flowering in vegetable crops.

Factor	Category	Effect on Flowering
Photoperiod	Environmental	Regulates induction via florigen; Short day, Long day, or day-neutral responses
Temperature	Environmental	Low temperature (vernalization) promotes biennial crops; high temperature affects pollen viability
Light Intensity	Environmental	Adequate intensity promotes flower initiation and fruit set
Water Availability	Environmental	Drought can trigger premature bolting; excess delays flowering
Gibberellins	Physiological/Hormonal	Promote floral initiation, stem elongation and FT gene expression
Cytokinins	Physiological/Hormonal	Stimulate meristem activity and flower bud formation

Factor	Category	Effect on Flowering
Auxins	Physiological/Hormonal	Regulate floral organ development and assimilate transport
Ethylene	Physiological/Hormonal	Regulates sex expression in cucurbits; modifies floral gene expression
ABA	Physiological/Hormonal	Acts as flowering inhibitor under stress; delays floral transition
FT / Florigen	Genetic	Mobile signal produced in leaves; triggers flowering at shoot apex
CO (CONSTANS)	Genetic	Photoperiod sensor; activates FT when expressed in daylight
FLC	Genetic	Represses FT; suppressed by vernalization to allow flowering

3.1 Photoperiodism

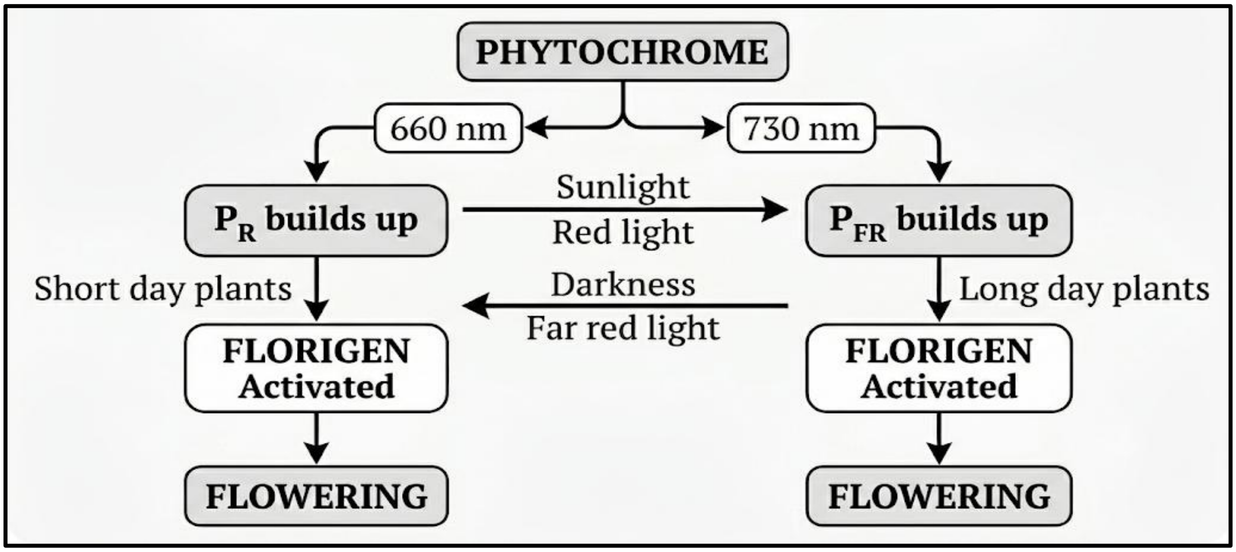
The phenomenon of photoperiodism was first discovered by American plant physiologists W.W. Garner and H.A. Allard in 1920. Photoperiodism refers to the physiological changes that occur in plants in response to the relative length of day and night. The classification of plants based on photoperiodic response is presented in Table 2. (Song et al., 2015).

Table 2. Classification of vegetable crops based on photoperiodic response.

Type	Day Length Required	Critical Factor	Examples
Short Day (SDP)	10-12 h light; 14-16 h dark	Dark period (must be continuous)	Soybean, onion, certain spinach varieties
Long Day (LDP)	14-16 h light	Light period	Radish, cabbage, sugar beet, spinach
Day Neutral (DNP)	5-24 h (any)	Not photoperiod-dependent	Tomato, brinjal, chilli, capsicum

In short day plants, the dark period is critical and must be continuous. Interruption of this dark period with even a brief exposure to red light (660-665 nm wavelength) prevents flowering. Conversely, in long day plants, the light period is critical and a brief exposure of red light during the dark period stimulates flowering. Day-neutral plants such as tomato, brinjal, chilli and capsicum can initiate flowering across a wide range of photoperiods without a specific photoperiodic stimulus. (Taiz et al., 2015).

Figure 1. Flowering in Short and Long day plants.

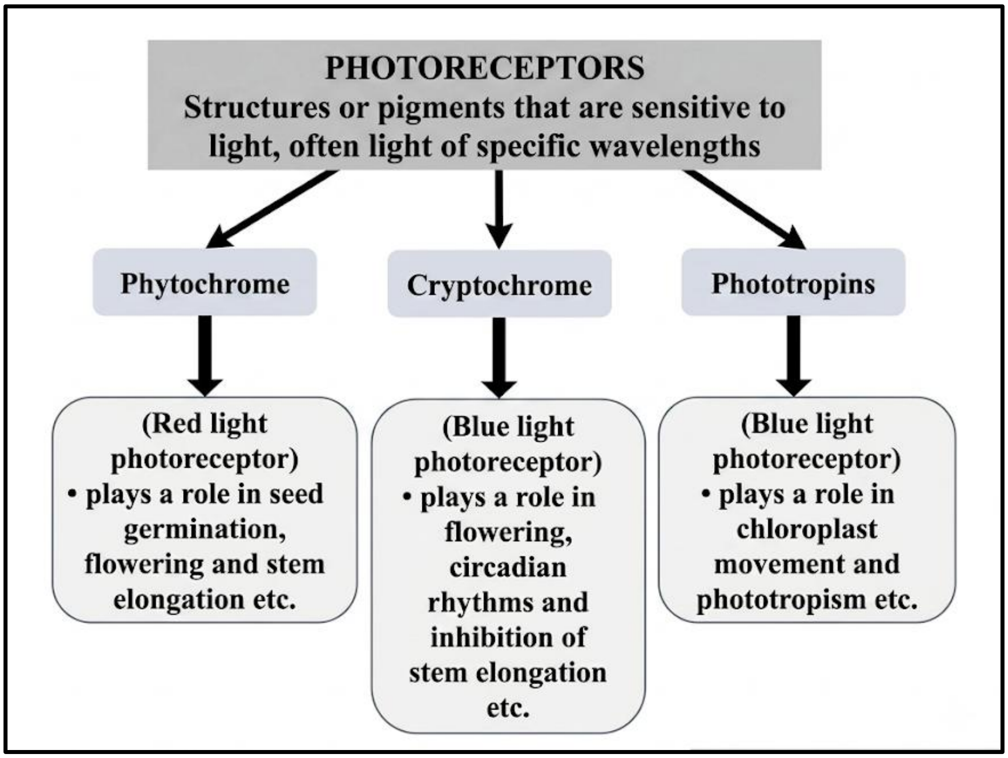


3.2 Mechanism of Photoperiodism — Florigen and Phytochrome

The perception of a suitable photoperiod by the leaves generates a floral stimulus known as florigen. Florigen is a mobile flowering signal produced in the leaves and transported through the phloem to the shoot apical meristem, where it triggers the transition from vegetative growth to reproductive growth.

Phytochrome, a biological proteinaceous pigment present in the plasma membrane, exists in two interconvertible forms: PR (inactive, absorbs red light at 660-665 nm) and PFR (active, absorbs far-red light at 730-735 nm).

Figure 2. Classification of Photoreceptors (Sarkar et al., 2024).



In short day plants, accumulation of PR in the long dark period activates florigen. In long day plants, PFR accumulated during extended light periods activates the flowering signal. (Sharma et al., 2023).

Three major classes of photoreceptors are involved in flowering regulation: (i) Phytochromes — red light photoreceptors involved in seed germination, flowering and stem elongation; (ii) Cryptochromes — blue light photoreceptors regulating flowering and circadian rhythms; and (iii) Phototropins — blue light receptors involved in chloroplast movement and phototropism (Sarkar et al., 2024).

3.3 Temperature — Vernalization and Heat Effects

Temperature acts as both a promotive signal and a stress factor depending on crop requirements and growth stage. Vernalization refers to the exposure of plants to low temperatures (0-10°C) for a specific period to induce flowering. This process is essential for biennial vegetable crops such as cabbage, celery, carrots and radishes. At the molecular level, vernalization operates via suppression of FLOWERING LOCUS C (FLC), a cold-repressive gene that normally blocks FT expression. Once temperatures rise after the cold period, FLC remains epigenetically silenced, allowing flowering to proceed. (Lee, 2025).

High temperatures can either promote flowering in warm-season vegetables or inhibit it when temperatures exceed optimum levels. Tomato flowers optimally at 21-24°C, pepper at 20-28°C, eggplant at 21-27°C, and cucurbits at 25-30°C. Above these optima, flower abortion increases, pollen viability decreases, stigma receptivity is reduced, and fruit set declines. (Chaudhary et al., 2022).

3.4 Light Intensity

Light intensity functions as both an energy source through photosynthesis and as a developmental signal regulating the vegetative-to-reproductive transition. Low light intensity delays flowering, reduces flower initiation, impairs pollen viability and increases flower and fruit drop. Optimum light intensity enhances photosynthesis, promotes early and uniform flowering and improves fruit set and yield. (Wu et al., 2025).

3.5 Water Availability

Water stress can trigger premature bolting in some vegetable crops, especially during the critical transition to flowering. Drought-induced flowering has been reported in certain pepper and tomato cultivars. Conversely, excess water during early growth can promote excessive vegetative growth at the expense of flowering. Water stress during the flowering stage often causes flower drop, where the plant sheds blossoms to conserve moisture. (Khalid et al., 2022).

4. Physiological Factors — Role of Phytohormones

Plant hormones function as key regulators of flowering by integrating environmental cues with developmental signals. Gibberellins, auxins, cytokinins, ethylene and abscisic acid work in concert to regulate the shift from vegetative to reproductive growth as well as the commencement and retention of fruits. (Singh et al., 2026; Tao et al., 2024).

- Gibberellins: Promote floral initiation and stem elongation; enhance flowering (FT) gene expression; help overcome vernalization requirements in some crops.

- Cytokinins: Promote cell division in shoot apical meristems; stimulate floral meristem activity; enhance nutrient mobilization toward developing flowers.
- Auxins: Regulate floral meristem formation and flower organ development; influence assimilate transport toward developing flower buds.
- Ethylene: Modifies floral gene expression and alters hormonal balance; regulates sex expression, particularly in cucurbits.
- Abscisic Acid (ABA): Acts as a flowering inhibitor under stress conditions; delays floral transition by suppressing growth-promoting pathways; interacts with photoperiodic and temperature pathways (Tao et al., 2024).

5. Genetic Control of Flowering

5.1 Circadian Clock and Flowering Genes

The circadian rhythm is an endogenous, self-sustained biological clock that generates approximately 24-hour cycles in physiological, biochemical and molecular processes of plants. Plants use the circadian clock together with environmental signals such as light and temperature to determine the appropriate season for flowering. (Dunlap et al., 2004).Regulation of flowering involves interaction between the circadian clock, photoreceptors and downstream flowering genes. The key genes involved are presented in Table 3.

Table 3. Key flowering genes and their functions in the circadian flowering pathway (Song et al., 2015; Venkat and Muneer, 2022).

Gene	Expression Time	Main Function	Flowering Role
CCA1	Morning	Clock regulator	Controls timing of flowering signals
LHY	Morning	Clock regulator	Synchronizes photoperiod response
TOC1	Evening	Clock feedback regulator	Maintains circadian rhythm
CO	Late afternoon/Evening	Photoperiod sensor	Activates FT gene
FT	Leaves	Florigen (mobile signal)	Induces flowering at shoot apex
FLC	Throughout	Flowering repressor	Suppressed by vernalization to allow flowering

5.2 Integration of Circadian Clock and Flowering Pathway

CONSTANS (CO) serves as the primary photoperiodic flowering regulator, acting like an alarm clock gene. The accumulation and stability of CO protein depend on the coincidence between circadian-controlled gene expression and light availability. When CO expression occurs during daylight, the protein remains stable and activates FT expression. When CO accumulates in darkness, it is degraded, preventing flowering induction. (Venkat and Muneer, 2022).

FLOWERING LOCUS T (FT) functions as the florigen, a mobile flowering signal synthesized in leaves and transported to the SAM. Once FT reaches the meristem, it interacts with the bZIP transcription factor FD and activates floral meristem identity genes including LEAFY (LFY) and APETALA1 (AP1), initiating flower development. (Venkat and Muneer, 2022; Singh et al., 2026).

FLOWERING LOCUS C (FLC) acts as a brake on the flowering pathway by repressing FT gene expression. It is suppressed epigenetically by vernalization through Polycomb Repressive Complex 2 (PRC2)-mediated H3K27me3 histone modification, enabling flowering after prolonged cold exposure. (Lee, 2025).

6. Case Studies

6.1 Case Study 1: Effect of Plant Growth Regulators on Flowering and Sex Expression in Cucumber cv. Malini (Sapkota et al., 2020)

An experiment was conducted to evaluate the effect of different PGRs on the growth, flowering behaviour, sex expression (male: female ratio), and fruit yield of the cucumber cv. Malini in a RCBD. PGRs ($AgNO_3$, ethephon, GA_3, NAA at varying concentrations) were sprayed three times starting at the 2-4 true leaf stage.

Table 4. Effect of PGR treatments on sex expression and yield of cucumber cv. Malini.

Treatment	Concentration	Effect on Flowering/Yield
GA_3	300 ppm	Highest fruit number, best yield (recommended)
GA_3	500 ppm	Most female flowers, lowest male:female ratio
Ethephon	250-500 ppm	Increased femaleness (more pistillate flowers)
$AgNO_3$	250-500 ppm	Promoted male flower formation
Control	Water spray	Baseline sex ratio and yield

Among all treatments, GA_3 at 300 ppm was the most effective, producing the greatest fruit set, highest number of fruits per plant, and maximum fruit yield. It can be recommended for commercial cucumber production.

6.2 Case Study 2: Induction of Staminate Flowers in Gynoecious Cucumber (Yadav and Singh, 2025)

A study was conducted on the gynoecious, parthenocarpic cucumber variety Pusa Seedless 6 to identify effective chemical treatments to induce staminate flowers, which are essential for hybrid seed production. Foliar sprays of GA_3, $AgNO_3$, and $Ag_2S_2O_3$ at varying concentrations were applied starting at the 2-4 true leaf stage at 7-day intervals.

Table 5. Effectiveness of chemical treatments for staminate flower induction in gynoecious cucumber.

Treatment	Concentration	Male Flowers/Plant	Recommendation
$Ag_2S_2O_3$	300 ppm	Highest	Best — recommended
$Ag_2S_2O_3$	500 ppm	High	Effective
$AgNO_3$	300-500 ppm	Moderate	Useful
GA_3	500-1000 ppm	Low-Moderate	Less effective

Treatment	Concentration	Male Flowers/Plant	Recommendation
Control	Distilled water	None	No male flowers induced

Silver thiosulphate ($Ag_2S_2O_3$) at 300 ppm was the most effective treatment. It suppressed the feminizing effect of endogenous ethylene and promoted abundant male flower formation, with earlier flowering, a longer flowering span, more staminate nodes, and the highest number of male flowers per plant.

7. Conclusion

Flowering in vegetable crops is regulated by the interaction of environmental cues and genetic pathways, with photoperiod and temperature acting as the most important external signals controlling the transition from vegetative to reproductive growth. The circadian clock integrates day length information through genes such as CCA1, LHY, TOC1, CO and FT, enabling plants to perceive seasonal changes and flower at the most favorable time for reproduction.

Photoperiodic responses differ among crop species, resulting in short-day, long-day, and day-neutral flowering behaviors that directly influence crop adaptation, productivity and geographical distribution. Phytohormones including gibberellins, cytokinins, auxins, ethylene and florigen-related signals interact with flowering genes, coordinating floral induction, flower development and reproductive success in vegetable crops.

Practical case studies demonstrate how manipulation of photoperiod, temperature, and plant growth regulators can substantially enhance flowering time, sex expression, fruit set and ultimately crop yield. Recent advances in molecular genetics and environmental physiology have improved understanding of flowering regulation, providing opportunities to develop climate-resilient, high-yielding vegetable varieties through precision breeding and crop management.

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