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Photoperiodic LED Pulse Regimes for Targeted Pigmentation and Vase Life in Floriculture: A Comprehensive Review

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Light is a primary environmental signal regulating plant growth, secondary metabolism, flowering, and senescence. In floriculture, light quality and photoperiod critically influence flower colour, pigment accumulation and postharvest longevity. While the effects of continuous spectral light treatments using light-emitting diodes (LEDs) are well documented, the role of temporal light modulation, including pulsed and time-patterned LED regimes, remains poorly explored in ornamental crops. Pulsed light introduces an additional regulatory dimension by altering frequency, duty cycle and intermittency without changing total photon delivery. This review synthesizes existing knowledge on plant photoreceptors, temporal light perception, pigment biosynthesis, antioxidant regulation and postharvest flower physiology, drawing evidence mainly from horticultural and plant physiological studies. The review highlights the potential of photoperiodic LED pulse regimes to enhance anthocyanin and carotenoid accumulation and to delay senescence through improved antioxidant responses. Current limitations, research gaps and future experimental directions for floriculture crops are discussed, with emphasis on sustainable, non-chemical approaches for improving flower quality and vase life.

Keywords: Pulsed LED lighting; temporal light modulation; photomorphogenesis; anthocyanins; carotenoids; postharvest physiology; vase life; floriculture

Introduction

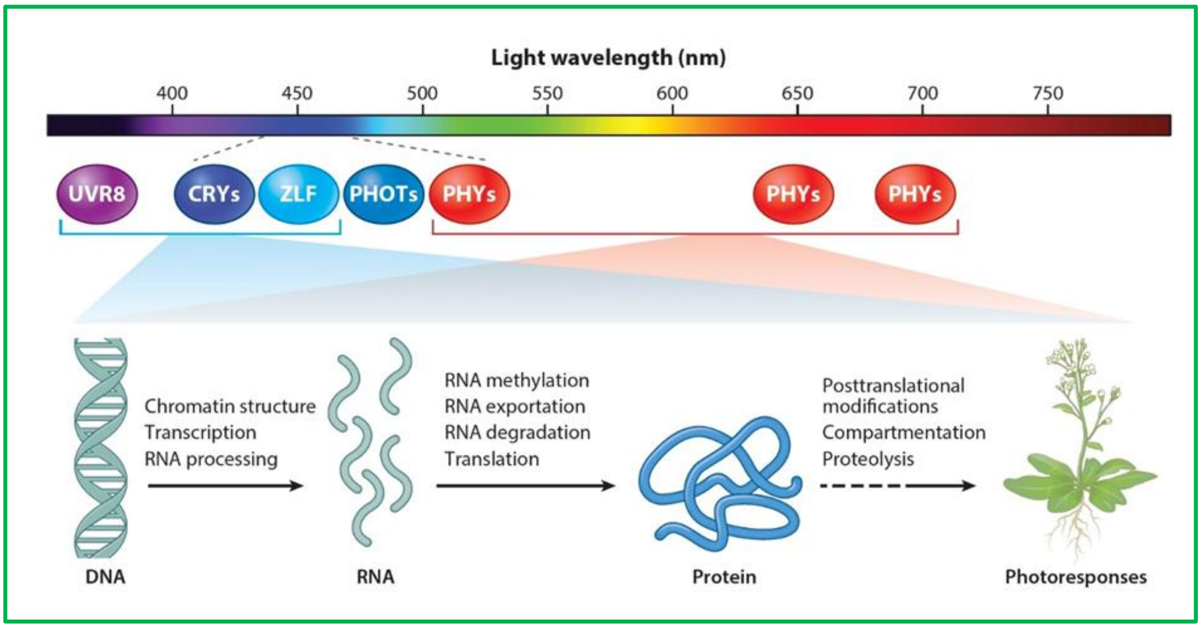
Light regulates nearly every aspect of plant growth and development, functioning both as an energy source for photosynthesis and as an informational signal that controls morphogenesis, metabolism and senescence. In floriculture crops, light strongly affects traits of commercial importance, including flower colour intensity, stem elongation, flowering time and postharvest longevity (Taiz *et al*., 2015; Olle and Viršile, 2013). Traditionally, research and commercial practices have focused on optimizing light intensity, photoperiod and spectral composition.

The widespread adoption of LED technology in controlled-environment agriculture has transformed horticultural lighting by enabling precise spectral control and high energy efficiency (Massa *et al*., 2008). Beyond spectral manipulation, LEDs also allow accurate temporal control of light delivery, including pulsed or intermittent illumination. Temporal light modulation refers to the delivery of light in discrete ON–OFF cycles, defined by frequency, duty cycle and pulse width, while maintaining a constant daily light integral (DLI).

Although pulsed LED lighting has been studied mainly in leafy vegetables to reduce energy consumption, accumulating evidence indicates that plants respond to temporal light patterns at physiological and biochemical levels (Kanechi *et al*., 2016; Carotti *et al*., 2021). These findings suggest that temporal light patterns may serve as regulatory signals capable of modulating secondary metabolism, pigment biosynthesis and stress responses. However, systematic investigation of pulsed or time-patterned LED regimes in floriculture crops, particularly in relation to flower pigmentation and vase life, remains limited. This review critically examines the theoretical basis, available evidence and future potential of photoperiodic LED pulse regimes for improving floricultural crop quality.

Plant Photoreceptors and Temporal Light Perception

Plants perceive light through specialized photoreceptors, including phytochromes, cryptochromes, phytotropins and UVR8, which together regulate photomorphogenic responses and metabolic pathways (Chen *et al*., 2004). These photoreceptors differ in their spectral sensitivity and kinetic properties, enabling plants to integrate not only light quality and quantity but also temporal characteristics of illumination.



(https://research.mcdb.ucla.edu/Lin/)

Phytochromes and Red/Far-Red Pulses

Phytochromes exist in two photo interconvertible forms: the inactive Pr form and the biologically active Pfr form. The balance between these forms depends on both light exposure and dark intervals, allowing phytochromes to act as temporal sensors (Franklin and Quail, 2010). Pulsed red or far-red light can produce different phytochrome activation states compared with continuous illumination, even at identical photon doses, potentially altering downstream gene expression.

Blue-Light Photoreceptors and Signal Dynamics

Cryptochromes and phototropins perceive blue light and regulate processes such as flavonoid biosynthesis, stomatal movement and phototropism (Lau and Deng, 2010). These receptors exhibit rapid activation and deactivation kinetics, suggesting that intermittent blue-light pulses could differentially modulate transcriptional networks involved in secondary metabolism, including anthocyanin biosynthesis.

Temporal Light Modulation: Concepts and Parameters

Temporal light modulation involves varying the timing of light delivery rather than its total quantity. Key parameters include pulse frequency, duty cycle and pulse width. Studies typically maintain constant DLI to isolate temporal effects from differences in total photon input (Miliauskienė *et al*., 2021).

The theoretical basis for temporal modulation lies in the non-linear nature of plant signal transduction. Photoreceptor activation, transcription factor dynamics and metabolic enzyme activities operate on multiple time scales. Consequently, plants may respond differently to pulsed versus continuous light, even when cumulative light energy is equal.

Pulsed LED Lighting and Plant Growth

Early studies on pulsed lighting focused on photosynthetic efficiency and energy savings. Kanechi *et al*. (2016) demonstrated that leaf lettuce grown under pulsed LED light maintained photosynthetic performance comparable to continuous illumination. Similarly, Miliauskienė *et al*. (2021) reported that multispectral pulsed LED lighting improved biomass accumulation, leaf pigmentation and antioxidant activity in lettuce.

These findings suggest that photosynthesis can integrate intermittent photon delivery effectively and that pulsed light does not inherently reduce growth. Instead, pulsed regimes may create transient physiological states that influence downstream metabolic processes.

(https://www.lighting.philips.ca/support/cases/horticulture/florensis)

Effects of Pulsed Light on Secondary Metabolism and Pigmentation

Anthocyanin Biosynthesis

Anthocyanins are key pigments responsible for red, purple, and blue coloration in flowers. Their biosynthesis is strongly regulated by light through transcriptional control of enzymes such as chalcone synthase, dihydroflavonol reductase and anthocyanidin synthase (Jaakola, 2013). Light-responsive transcription factors, including HY5 and MYB proteins, mediate these effects.

Carotenoids and Antioxidant Compounds

Carotenoids contribute to yellow and orange flower coloration and function as antioxidants. Light regulates carotenoid biosynthesis through both photosynthetic and signalling pathways (Olle and Viršile, 2013). Carotti *et al*. (2021) reported changes in antioxidant capacity and phenolic content in lettuce under different LED switching frequencies, indicating that temporal modulation can affect broader secondary metabolism.

Temporal Light, Oxidative Signalling, and Antioxidant Responses

Reactive oxygen species (ROS) are produced during photosynthesis and act as both damaging agents and signalling molecules. Moderate ROS signalling can activate antioxidant defence systems and secondary metabolite production (Foyer and Noctor, 2005). Pulsed light may generate transient fluctuations in photosynthetic electron transport, leading to controlled ROS signals that enhance antioxidant enzyme activities.

Enhanced antioxidant capacity is particularly important for floral tissues, as oxidative stress accelerates petal senescence and limits vase life (van Doorn and Woltering, 2008).

Thus, temporal light modulation may indirectly extend vase life by strengthening antioxidant defences.

Circadian Regulation and Timing of Light Pulses

Plants possess endogenous circadian clocks that regulate gene expression and metabolism. Light pulses delivered at different circadian phases can elicit distinct physiological responses (Harmer, 2009). Secondary metabolism, including anthocyanin synthesis, is often circadian-regulated, suggesting that the timing of pulsed light relative to the circadian cycle may be critical for maximizing pigment accumulation. This aspect has not been systematically explored in floriculture but represents a promising research direction for optimizing LED pulse regimes.

Postharvest Light Treatments and Vase Life

Vase life of cut flowers is influenced by carbohydrate depletion, water relations, ethylene sensitivity and oxidative damage (van Doorn, 2012). Recent studies indicate that light exposure during postharvest storage or display can modulate these processes.

Horibe and Shimokawa (2020) reviewed the use of light stimuli as a postharvest technology and reported that specific wavelengths can delay senescence and improve flower quality. Rezai *et al*. (2020) showed that red LED illumination reduced weight loss and delayed flower opening in cut roses. However, these studies primarily used continuous light and the effects of pulsed or time-patterned postharvest illumination remain largely unexplored.

Knowledge Gaps and Research Opportunities

Despite promising evidence, several gaps remain:

1. Limited studies on pulsed LED effects in ornamental flowers.
2. Lack of mechanistic understanding linking temporal light signals to gene expression in floral tissues.
3. Minimal research on postharvest pulsed light applications.
4. Absence of studies on complex or non-periodic temporal light patterns.

Addressing these gaps could lead to sustainable, non-chemical strategies for improving flower quality and longevity.

Future Research Directions

Future studies should focus on:

- Systematic evaluation of pulse frequency, duty cycle, and timing in ornamental species.
- Integration of physiological, biochemical, and molecular analyses.
- Exploration of circadian-based pulse scheduling.
- Development of postharvest LED systems optimized for temporal modulation.

Conclusion

Photoperiodic LED pulse regimes represent a promising yet underexplored tool in floriculture. Existing evidence from horticultural crops suggests that temporal light modulation can influence secondary metabolism and antioxidant capacity without compromising growth. Applying these principles to ornamental crops offers opportunities to enhance flower pigmentation and extend vase life using sustainable lighting strategies. Rigorous experimental research is required to translate this concept into practical floriculture applications.

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