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Proper quality of LED light to produce high-quality ornamental plants in controlled environment agricultural systems: A review

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Review Article

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ABSTRACT

Light plays a crucial role in plant growth and development, serving as both the main energy source for photosynthesis and an external signal. The use of artificial light (AL) for production of ornamental plants is growing nowadays. It is employed to enhance yield, prolonging the production season, improving product quality, and serve as photoperiodic light for regulating flowering in day length-sensitive species. Achieving successful plant growth with artificial lighting requires a careful balance of quality, intensity, and photoperiod. The numerous benefits of Light-emitting diodes (LED) technology make it an ideal choice for the ornamental industry, offering unparalleled energy efficiency, durability, compact size, long-lasting lifespan, and minimal heat emission. With the ability to carefully manipulate light quality to impact specific characteristics of plants such as architecture, pigmentation, and flowering, it is no wonder the industry is paying close attention to the potential of controlling the growing environment. By utilizing lighting technology, growers can gain various positive outcomes, such as strategic production (with options for early flowering, continuous production, and consistent yields), enhanced plant structure (improved root growth and size, stem elongation, etc), determination of leaf and flower color, and elevated product quality. When it comes to lowering energy and chemical usage (specifically pesticides and plant growth regulators), LED technology provides the floriculture industry with a solid and eco-friendly alternative. In this review paper the significance of ornamental flower production in controlled environment agriculture (CEA), together with the proper lighting strategies for production of ornamental plants are discussed.

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1. Introduction

The ornamental industry includes a very broad variety of plants, such as cut and pot floriculture crops, ornamental grasses and ornamental trees and shrubs, for their aesthetic values. The significance of floriculture's economic influence is noteworthy. The global market for flowers and ornamental plants was valued at USD 52,384.85 million in 2022, and over the forecast period, it is anticipated to increase at a Compound Annual Growth Rate (CAGR) of 7.28% from 2023 to 2028 (Trivellini *et al*., 2023). With a market share of almost 47%, Europe leads the Asia-Pacific region in ornamental sales, followed by the US with 13.5% and Asia-Pacific (20%) (Trivellini *et al*., 2023). Even though the ornamental plant market is rather large economically, the COVID-19 epidemic and the ensuing public shutdown events severely harmed its global supply chain, as they do with many non-essential items and sectors (Bulgari *et al*., 2021). Artificial light in controlled environments, such as soilless systems, greenhouses, and indoor farming, can be used to maximize the output of ornamentals. Light is necessary for the growth, development, morphology and functioning of plants because it initiates response pathways and speeds up photosynthetic CO_2 absorption (Xu, 2019). Artificial lighting provides energy for photosynthesis, controls crop morphogenesis, and manages blooming processes. It can be employed as a sole or supplemental light source. Compared to conventional lighting systems, light-emitting diode (LED) technology has some advantages such as increased energy efficiency, economic effectiveness, and the ability to set high light intensities (Singh *et al*., 2015). Therefore, modifying the growing light environment garnered a lot of attention from the scientific and commercial sectors by establishing completely controlled environment agriculture (CEA) systems for the production of crops in a season-independent and continuous production manner. Combining different parameter settings in the lighting environment is now feasible because to the use of contemporary LED sources in CEA production processes (Lastochkina *et al*., 2022). Utilizing LEDs can shorten plant growth times and increase yield and quality, among other advantages (Appolloni *et al*., 2021). In regions with little natural light, adding LED lighting can improve greenhouse production's sustainability (Marcelis *et al*., 2019). With more light from LEDs with certain spectra, even plant species that have not historically required high light levels, such as anthurium and bromeliads, have demonstrated better flower induction and emergence (Javadi Asayesh *et al*., 2021). LEDs have been used in postharvest studies to assess the effects of light quality and intensity on the vase life or shelf-life of flowers because they can provide precise light qualities close to horticultural commodities (Aalifar *et al*., 2020; Aliniaeifard *et al*., 2020). The daily light integral (DLI), which is the result of photoperiod and appropriate light intensity, presents difficulties in the manufacture of CEAs. These elements have a direct bearing on plant development, energy usage, and the CEA system's overall sustainability. CEA systems, various light characteristics such as spectrum, intensity, and photoperiod are manipulated to optimize the lighting environment based on specific production goals, such as biomass increase, secondary metabolite production, or shelf-life improvement. The spectral composition of the light environment significantly impacts plant responses. For instance, red and blue light wavebands are primarily absorbed by chlorophyll pigments and serve as the main energy source for electron excitation in the photosynthetic apparatus of plants (Heldt and Piechulla, 2011). These two wavelengths are frequently used for plant production in controlled environments because the principal absorption spectra of chlorophyll pigments lie between those of blue and red light (BR) (Seif *et al*., 2021). A significant body of literature focuses on how plants perceive and respond to red (R), far-red (FR), and the red/far-red ratio, which is mediated by phytochromes. Employing AL on ornamental plants is gaining popularity for increasing yield, prolonging the production cycle, enhancing product quality, and managing flowering in species sensitive to day length. Effective artificial lighting for plant growth requires balancing factors such as light quality, intensity, and photoperiod (Goto, 2003). Light quality pertains to the spectral makeup of the light source. Better control over plant growth and development is made possible by LEDs' compliance with particular criteria for leaf optical features, including dynamic photosynthetic activity and biochemistry processes (Karabourniotis *et al*., 2021). This review provides an overview of the use of LED lighting technology for growing and producing ornamental crops. Also, this review explores how LED illumination can enhance ornamental market innovation and provide growers with guidelines to improve production quality (Table 1).

2. History of LED lighting

The discovery of the LED dates back to the early days of wireless technology when there was limited understanding of semiconductors and their potential for generating light. Appropriate LED light to replace traditional light bulbs was a time-consuming endeavor. Even after finding the right white light or color temperature, the brightness fell short. Initially, LEDs were mainly used in solid-state or electronic applications. In 1962, Nick Holonyak Jr. from General Electric created the first practical visible spectrum LED light. In 1972, Holonyak's graduate student, M. George Craford, invented the first yellow LED and made red and red-orange LEDs that were 10 times brighter. The introduction of green LEDs expanded applications by utilizing three primary colors. A significant advancement came in 1994 when Shuji Nakamura and colleagues at Nichia, a Japanese company, produced a high-brightness blue LED light. This development was crucial not only for various reasons but also because when combined, blue, green, and red LED lights create white light, as perceived by the human eye. Nakamura's invention laid the groundwork for future white LED light production, leading to his recognition with the Millennium Technology Prize in 2006. However, it wasn't until around 2008 that LED technology advanced enough to produce light with the necessary intensity for residential and commercial use. The initial red LED was created in 1962, with the first application in plant growth studies occurring in 1988. NASA initiated a project to implement LED-illuminated plant growth systems in space to further this research. Japan pioneered commercial LED use for plant cultivation in 2000, sparking the widespread adoption of LEDs in horticulture. Today, LEDs find diverse applications in agriculture, horticulture, and crop preservation. Research on LED lighting's impact on bioactive compound accumulation and biomass production primarily occurs in controlled growth chambers devoid of natural light. The benefits of LED technology include efficient lighting with minimal heat emission, leading to reduced energy expenses; precise light distribution due to the microchip nature of LEDs; low energy consumption; extended lifespan; safe handling; compact size; cold light emission suitable for greenhouse environments; customizable wavelength selection for specific processes; and the ability to achieve desired colors without additional filters while maintaining illumination intensity.

3. Light Spectrum effects on ornamentals

Plants capture light information through photoreceptors containing specific light-sensitive pigments that absorb radiation of particular wavelengths (Figure 1). They respond to various light qualities for photosynthesis and photomorphogenesis, influencing their shape and development. Photosynthetically active radiations (PAR) in horticulture lighting support plant photosynthesis within the 400–700 nm light spectrum range. However, the PAR with peaks in the red and blue spectral ranges, incorrectly suggests that the green spectrum is irrelevant for photosynthesis, differing from the McCree Curve range of 280 nm to 800 nm. Electromagnetic radiation essential for photomorphogenesis falls outside the PAR range, approximately from 380 nm to 850 nm. Current sensors in measuring devices cannot detect UV, far-red wavelengths, or wavelengths beyond the visible spectrum crucial for plant growth, solely focusing on PAR. Excluding vital light wavelengths during growth causes an imbalance in plant processes, hindering their development. Modern LEDs, commonly used for being energy-efficient and non-thermal, lack beneficial thermal IR light wavelengths supporting human and plant health. The preference for non-thermal LEDs ensures prolonged luminaire lifespan by reducing the impact on electronic components. The rising use of ornamental plants indoors highlights the importance of developing suitable action spectra and measurement tools to optimize conditions for human and plant well-being (Zielinska-Dabkowska *et al*., 2019).

Cuttings are prone to quick drying, and controlling transpiration can be accomplished by using a balanced light spectrum. Stomatal opening response is primarily triggered by blue light but is amplified in the presence of a strong red-light background (Yang *et al*., 2020). For example, in Impatiens × hybrida hort., environments with a higher percentage of red light and a lower percentage of blue light have been observed to increase the number of trichomes, which are structures associated with reducing water loss through transpiration (Kobori *et al*., 2022).

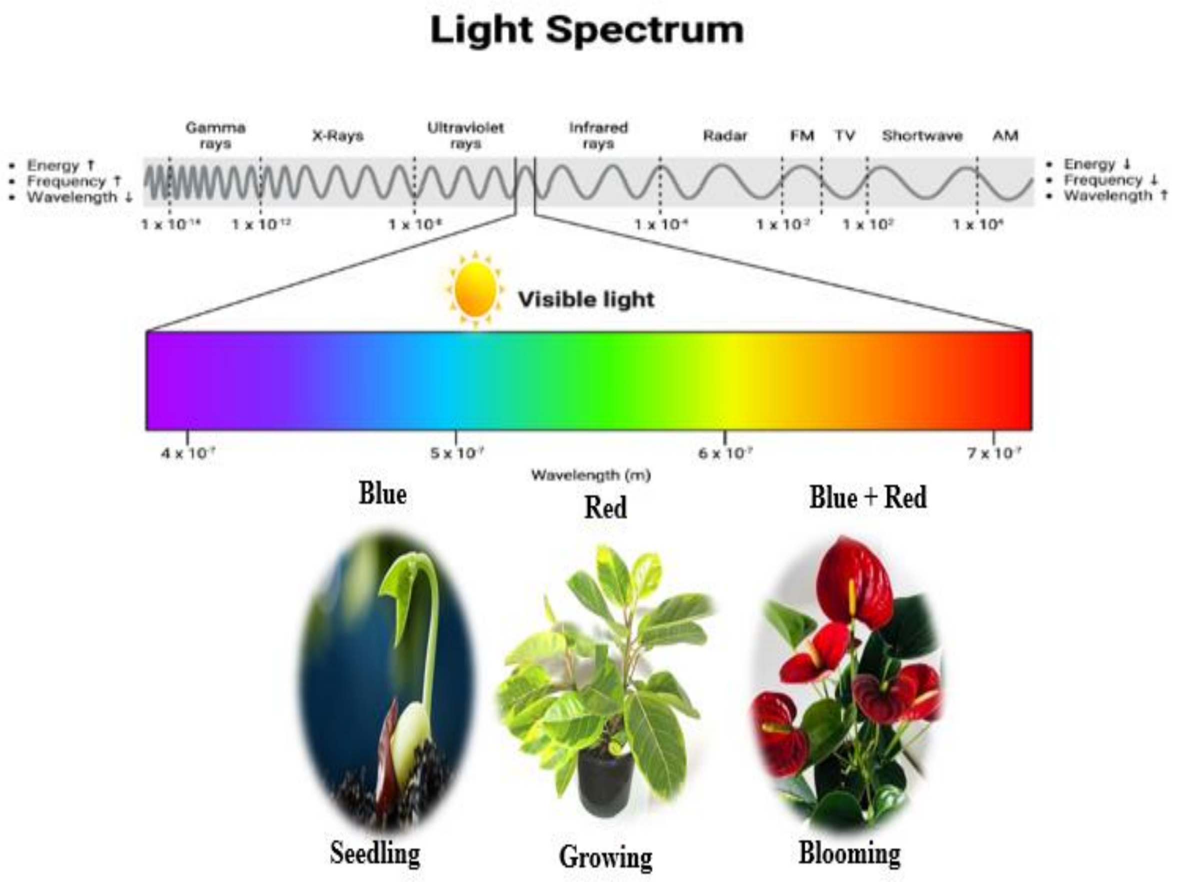


Figure 1. Effects of light spectrum on ornamental plant

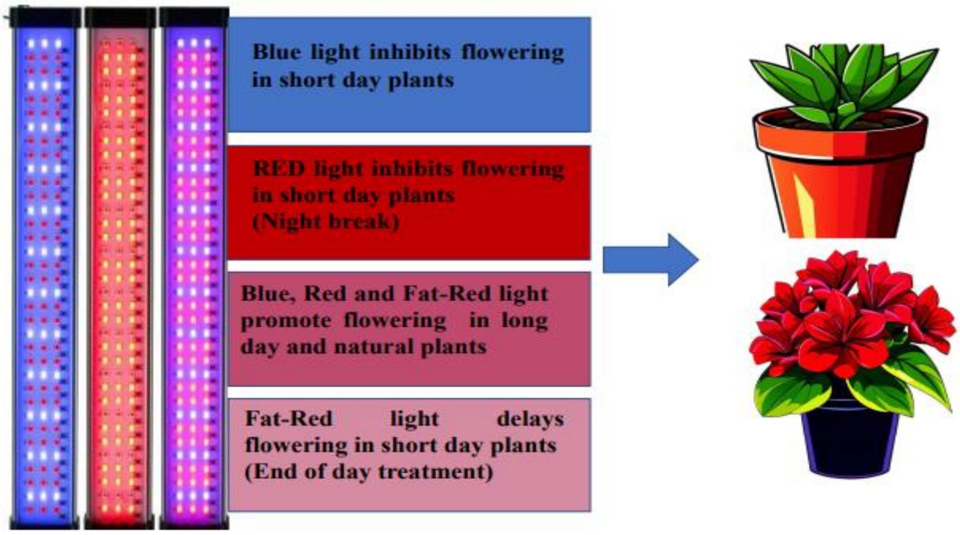
Table 1. Main effects of light quality on various ornamental plant species.

Light quality	Species	Main Effect of Lights on Plant	References
B light	Lily Bulbs	Concentrated more biomass on the flowers, resulting in faster flowering and extended floral life all crucial qualities for the commercial production of lily flowers.	(Reut *et al*., 2024)
R + B: 70 % R + 30 % B	Lily Bulbs	Achieving high-quality lily bulbs with LED artificial lighting	(Reut *et al*., 2024)
TB (TLD lamps + B LEDs), TR (TLD lamps + R LEDs), and TBR (TLD lamps + B and R LEDs).	*Tradescantia zebrina* and *Chlorophytum comosum*	Both species exhibited higher root, shoot, and total dry weights when exposed to B LED lighting. Chlorophyll concentration demonstrated species-specific responses to monochromatic or mixed RB LEDs. The maximum photosynthetic rate was recorded with the combination of mixed R-B LEDs and TLD lamps. Incorporating B LEDs led to enhanced production of ornamental foliage in the species.	(Horibe, 2020)
RB: 70:30 %	Rose plants	Highest anthocyanin concentration	(Bayat *et al*., 2018)
R: B (R90B10)	Cut Rose	Enhanced growth, carbohydrate levels, photosynthetic capacity, and cut rose production.	(Davarzani *et al*., 2023)
BR = (50:50)	*Crocus sativus*	The yield of saffron flowers in terms of fresh and dry weight of flowers and stigmas, as well as blossom number (up to 1.97 per corm).	(Eftekhari *et al*., 2023)
B Right	*Crocus sativus*	Improvement Flowers morphological properties, highest content of total carotenoids, anthocyanins and flavonoids and Expression of genes involved in crocin production (CsCCD2, CsALDH31l, and CsUGT2).	(Moradi *et al*., 2022)
R, B or FR: (660, 440 and 735)	*Hypoestes phyllostachya, Guzmania lingulate* and *Cryptanthus carnosus*	Improvement for the anthocyanin content	(De Keyser *et al*., 2019)
R:B light (50:50)	*Lactuca sativa* L	Red pigmentation in plants is enhanced when they are grown under low greenhouse daily light integrals (DLIs) <10 mol·m^{-2}·d^{-1}.	(Owen and Lopez, 2019)
R:B light (50:50)	Pelargonium and Pennisetum	Improved leaf coloration when plants were cultivated in a greenhouse with a low DLI of ≤ 9 mol·m^{-2}·d^{-1}.	(Owen and Lopez, 2017)
R (660 nm), B (440 nm),	Rosa	ater uptake and evaporation rates were increased; however, the quality of cut	(Horibe, 2020)

W (white)		roses under red light treatment remained unchanged.	
B 450–495 nm	*Chrysanthemum*	Enhanced formation of roots, Enhanced photosynthesis	(Kurilčik *et al.*, 2008)
R 620–760 nm	*Euphorbia milii*	Flowering percentage is reduced	(Dewir *et al.*, 2006)
R (665 nm) + B (466 nm) Ratio R/B 1:1	*Rehmannia glutinosa*	Enhanced photosynthesis	(Cui et al., 2000)
R + FR	*Euphorbia milii*	Enhanced Flowering	(Dewir *et al.*, 2006)
B+ FR	*Euphorbia milii*	Enhanced Flowering	(Dewir *et al.*, 2006)
R (650 nm) + B (440 nm) Ratio: 2,3:1	*Tripterospermum japonicum*	Best plant growth	(Moon *et al.*, 2006)
R (660 nm) + B (450 nm) Ratio B/R = 2:1	*Dondrobium officinale*	Enhanced shooting	(Lin *et al.*, 2011)
20:80 (R4B); 40:60 (2R3B); 60:40 (3R2B); 80:20 (4RB); and (W) (100%).	*Lilium spp*	2R3B decreased the days to harvest maturity and flower height. Control enhancements were observed in the subsequent aspects: R4B = leaf area, tepal color; 3R2B = vase life; and 4RB = plant height, flower diameter, and days to maturity count.	(Flores-Pérez *et al.*, 2021)

4. Photoperiod and light quality effects on ornamentals

Phytochrome photoreceptors control stem elongation and flowering in photoperiodic plants. Phytochromes have R (600-700 nm) and FR (700-800 nm) absorbing forms (PR and PFR, respectively) (Smith, 1994). The R to FR light ratio affects phytochrome photoequilibria (PFR/PR+FR), influencing flowering in photoperiodic crops and stem extension in shade-avoiding plants. A low Pfr/Pr+fr ratio stimulates stem growth and flowering in long-day plants (LDPs) such as petunia (Runkle and Heins, 2005). Hence, many LDPs flower more rapidly under artificial lighting rich in FR light, especially towards the end of the photoperiod (Downs and Thomas, 1982). Plants grown under light deficient in FR, can delay flower initiation and development in certain plant species such as snapdragon, bellflower, coreopsis, petunia, pansy, and black henbane (Runkle and Heins, 2003). LDPs can be induced to flower when the natural day length is short by providing artificial lighting at the end of the day (EOD) (day extension) or during the middle of the night (night interruption, NI) to create long days (LD) (Fig 2). NI lighting is generally more effective for inducing flowering in LDPs compared to day extension, even if the intensity and duration of the supplemental lighting are equal (Thomas and Vince-Prue, 1996).



Blue light inhibits flowering in short day plants

RED light inhibits flowering in short day plants (Night break)

Blue, Red and Fat-Red light promote flowering in long day and natural plants

Fat-Red light delays flowering in short day plants (End of day treatment)

Figure 2. Effects of different lighting strategy on flowering of ornamental plants

While adding FR towards the EOD is an effective way to encourage stem elongation (Yang *et al*., 2012), there is not much data on whether R:FR in a greenhouse can be deliberately changed to regulate growth in the other direction. Additionally, there is a phenomenon that occurs outside close to sunset: the R:FR tends to decrease when the sun's height falls below 10–15° (Smth and Holmes, 1977). Chrysanthemum stem elongation was shown to be enhanced by low-intensity EOD light that resembled a twilight-like decline in R:FR (Lund *et al*., 2007). Increasing the R:FR at the end of the day would presumably hide the R:FR's normal decline and maybe even remove the stem elongation reaction that goes along with it. Height has been managed by using FR-absorbing filters during the day, but this has resulted in a loss of photosynthetic photon flux, which may also lower dry weight (Bachman and McMahon, 2006). When plants were moved to red-absorbing filters at the EOD, their height decreased by 16% and 22% for cucumbers and tomatoes, respectively, but not for watermelons. This reduction was seen in comparison to ambient illumination without any filter (Cerny *et al*., 2004). Although PPF remained unaltered for the most of the day using this strategy, moving plants beneath filters every morning and evening in an industrial setting would not be ideal. The effects of EOD by red light and EOD by far red light have been compared practically to ambient controls for stem elongation (Ilias and Rajapakse, 2005). Easter flower height is known to be sensitive to environmental conditions, such as temperature and EOD FR, although no EOD R treatment is known for Easter lilies in comparison to a control without EOD treatment (Blom *et al*., 2004).

Complex mechanisms, such as the light environment, are involved in both intrinsic and environmental aspects of flower induction and initiation. Many plant species, especially ornamental plants, sense variations in the light environment, such as photoperiod, light intensity, spectral composition, and direction, to coordinate their growth and development (García-Caparrós *et al*., 2020). Day-neutral (ND), short-day (SD), and LD plants comprise the majority of ornamental plant species. While SD plants are promoted during long nights, Flowering is induced when the night length is less than a certain threshold. Coordination of endogenous responses takes place in leaves during flowering, mediated by photoreceptor-driven complex gene regulatory networks (Erwin, 2005). The flowering transition is brought about by the inhibition of antiflorigenic FT (AFT)/TERMINAL FLOWER 1 (TFL1) and the overexpression of flowering locus T (FT) (Higuchi, 2018). Chrysanthemums grown under white light during photoperiod showed flowering under SD conditions interrupted by low-intensity blue or far-red light during the dark period, while no flowering occurred when interrupted by red light (Higuchi *et al*., 2012). The impact of supplemental blue light on flower bud formation and stem elongation in cut chrysanthemum 'Zembla'. The showed that 4 hours of monochromatic blue light following 11 hours of mixed red and blue light promoted internodal extension. Supplemental blue light could reduce the long days needed to achieve sufficient stem length during short-day induction (Jeong *et al*., 2014). Singh *et al* (2013), investigated the use of LEDs to induce flowering in *Chrysanthemum morifolium* cv. Zembla under artificial long-day conditions. Stem length was influenced by internode length and the attainment of the required number of leaves for diurnal response using LEDs. The diurnal response in chrysanthemum plants was strong in leaves, affecting the apex, with the shortest time for bud induction (28 days) observed under extended exposure to blue LEDs. Due to changed phytochrome levels, far-red treatments in garden chrysanthemums, and poinsettias, delayed the onset of flowering (Hisamatsu *et al*., 2008; Zhang and Runkle, 2019). This was observed in chrysanthemums, where short days of solar light followed by a 4 h extension with blue or red light were insufficient to affect flowering initiation (SharathKumar *et al*., 2021). FR light reversed the flowering inhibition mediated by phytochrome photoequilibrium. Flowering is greatly affected by blue light, which is brought on by cryptochrome and may be utilized to regulate the process. When blue light is more intense, it promotes flowering in LD plants while suppressing it in SD plants. For SD plants, the effects of green light might vary in timing and intensity, depending on the species. Depending on the species, region, and fluence rate, UV light can either accelerate or delay flowering. High UV radiation significantly impacts flowering quality (Bridgen, 2016).

In ornamental horticulture, the shape of potted plants is a vital factor in determining their visual appeal and hence commercial worth (Boumaza *et al*., 2010). To cultivate compact and dwarf pot plants of high quality, artificial lighting systems are employed. The use of FR-absorbing plastic filter aids in restricting stem elongation to some degree. For instance, the light filter Solatrol altered the R: FR ratio from 1.0 in natural light to over 3.8. When this filterwas utilized, plant height decreased by 30% in Petunia × hybrida and by 19% in *Impatiens walleriana* as compared to a standard polyethylene film. Conversely, in Petunia × hybrida, the flowering was delayed by one to two days (Fletcher *et al*., 2005). Similar outcomes regarding plant height were noted in *Euphorbia pulcherrima* when a more absorbing FR film was used (R:FR ratio = 5.7), with no alteration in plant branching (Mata and Botto, 2009). Observed 25.8% rise in the number of axillary stems in *Euphorbia pulcherrima* under a different absorbing FR plastic film (R:FR ratio = 1.74). In a greenhouse receiving natural light, supplemental red and blue LED lighting helps curb stem elongation (Clifford *et al*., 2004). For example, in *Euphorbia pulcherrima*, R (80%) and B (20%) LED lighting employed for 10 h daily reduced stem length by 34% compared to the supplemental photosynthetic lighting from high-pressure sodium lamps (Islam *et al*., 2012).

6. Shade avoidance syndrome and Red to Far Red ratio

Since adjacent foliage mostly transmits or reflects FR wavelengths, while absorbing a large proportion of red light for photosynthesis, a drop in incidence R:FR in the wild is suggestive of vegetative shade and/or competition (Wang *et al*., 2022). Plants integrate R:FR signals with other environmental factors such as temperature and light intensity (Blom and Kerec, 2003). When R:FR levels are too low, they can cause "shade avoidance syndrome," which refers to morphological changes that increase competition for light (Cheng *et al*., 2021). While various responses and threshold sensitivity to R:FR vary by species, such as thinner and flatter leaves, elongated petioles, or decreased branching, internode elongation is a reasonably typical response in higher plants (Demotes-Mainard *et al*., 2016). Through the phytochrome (P), plants react directly to the ratios of R and FR, hence controlling morphology, flowering, and germination. Phytochrome changes from its "inactive" red-absorbing state (Pr) to its "active" far red absorbing state (Pfr) following absorption of red light. It then quickly returns to Pr upon absorption of far-red light, or slowly in the absence of light (Rockwell *et al*., 2006). Plant responses are intimately correlated with phytochrome photoequilibrium, or the ratio of "active" phytochrome to total phytochrome (Pfr/P). For instance, a linear association between Pfr/Pr and internode elongation was found in *Chenopodium album* and *Fuchsia hybrida* (Vince-Prue, 1977). In addition to being connected with the R:FR, the Pfr/P may also be determined using the absorption spectra of Pr and Pfr and the spectral distribution of the light environment (Wang *et al*., 2022).

7. Tissue culture

Factors influencing the success of an *in vitro* culture system can be categorized into two main groups: chemical and physical. Chemical factors encompass the kind and concentration of growth regulators present in the medium, vitamins, antioxidants, solidifying and osmotically active substances, pH, etc. Physical factors mainly consist of thermal and light conditions in the growth room or phytotron. Unlike natural daylight, which consists of various light colors indistinguishable from the human eye, *in vitro* cultures cannot be sustained under natural lighting due to its instability and fluctuations throughout the day. Despite plants cultivated *in vitro* being generally heterotrophic or mixotrophic with limited photosynthetic activity (carbon is provided in the form of sugar in the synthetic medium), light still significantly impacts gene expression, primary and secondary metabolism, as well as the growth and development of explants – known as photomorphogenesis (Lin *et al*., 2011). This pertains particularly to the increasingly popular autotrophic culture system, which involves *in vitro* culture maintained under high light intensity and with low or zero sugar content in the medium. Inadequate light intensity can result in symptoms of etiolation, including chlorophyll deficiency, leaf deformities, and elongation and excessive water uptake in shoots. Conversely, excessive light exposure can trigger the production of damaging reactive oxygen species (ROS) (Solymosi and Schoefs, 2010). Therefore, both the quantity (intensity) and quality (spectrum composition) of light need to be carefully optimized. Red and blue light are crucial for the growth of plants in both *in vivo* and *in vitro* settings (Lin *et al*., 2013). To regulate plant photomorphogenesis, different types of LEDs emitting blue, red, or far-red light can be used at a low cost. The use of LEDs for growing plantlets could serve as a practical alternative to traditional lighting systems. Light intensity significantly influenced the dry weight, plantlet height, leaf number, leaf shape, and leaf area of in vitro-raised Phaius and Vanda (Soontornchainaksaeng *et al*., 2001). Enhanced growth of Cymbidium plantlets grown *in vitro* under super bright red and blue LEDs has been documented (Tanaka *et al*., 1998). Furthermore, the fresh and dry weight of plantlets was notably higher when cultivated under red and red plus blue LEDs, with leaves being the longest under red LEDs. Cultured nodal cuttings of in vitro chrysanthemum on MS (Murashige and Skoog medium) basal media for 35 days under six different light qualities: fluorescent (FL), B LEDs, R LEDs, RB LEDs, RFr LEDs, and BFr LEDs (BFr). The net photosynthetic rate was highest under RB, while fresh weight, dry weight, and leaf area were greatest under FL and RB, but decreased under BFr (Kim *et al*., 2004). The most substantial stem elongation was reported under R and RFr. Blue light plays a role in the synthesis of enzymes and chlorophyll (influencing total chlorophyll levels, the ratio of chlorophyll a and b, chloroplast development, and stomatal opening) (Lin *et al*., 2011). Furthermore, it activates the plant's defense mechanism against stress related to ROS activity (Mengxi *et al*., 2011). Conversely, red light plays a crucial role in shoot elongation, structural modifications, and phytochrome function (Shin *et al*., 2008). It is important to note that when present in excessive or insufficient amounts or when interacting with other elements, these light wavelengths might lead to an unfavorable distribution of light energy accessible for photosystems I and II, consequently impeding plant growth. In contrast to humans, plants exhibit lower sensitivity to green and yellow light. For instance, microshoots of *Plectranthus scutellarioides* cultivated under green light (with a peak at 530 nm) exhibited notably reduced root and shoot dry mass compared to those under different light conditions (Cho *et al*., 2019). This method is employed in gene banks to reduce the number of subcultures required and prolong the lifespan of plantlets *in vitro* culture. Plantlets are cultivated under light with a wavelength of 480 to 590 nm (Kulus, 2015).

8. Plant Architecture

The flexibility of LED technology allows for the creation of customized light recipes that may be used to manipulate the architecture of plants. The spectral composition of LED light has a significant impact on several plant properties, including branching, compactness, roots, and leaf expansion, which are all combined to form plant quality (distribution of energy across different wavelengths (Paradiso and Proietti, 2022). Combining R and B wavelengths makes sense for commercial plant production utilizing LED systems since photosynthetic pigments' absorption spectra primarily focus on blue (400–500 nm) and red (600–700 nm) and this allows for the exploitation of many regulatory mechanisms light (Li *et al*., 2020). Production of young ornamental plants is essential to the floriculture sector. Most manufacturing takes place throughout the winter or early spring. To satisfy the demand for spring and summer sales, the majority of production takes place in the winter or early spring. Regretfully, this coincides with a seasonally low outside photosynthetic daily light integral (DLI) that is significantly lower in greenhouses. Producing bedding plants is one of the most economical uses of LED lighting as it produces more standardized, compact, and superior annual young ornamental plants that are both marketable and resilient to transplant shock. Managing the growth of these commodities is crucial in the ornamental industry as it enhances their visual quality and physiological condition. Numerous studies have utilized red and blue light to examine their impact on plant morphology and anatomy. Generally, R and B LED lights influence physiological and morphological characteristics, including stomatal openings, plant height, chlorophyll biosynthesis, stem elongation, branching, leaf expansion, and reproduction (Paradiso and Proietti, 2022). Both supplementary and primary sources of LED lighting, featuring blue radiation against a red backdrop, restrict extension growth and leaf expansion when compared to growth under natural light supplemented with an HPS lamp or cool white fluorescence (Li *et al*., 2020). This approach offers an efficient non-chemical method to regulate the height of various bedding plant species (Randall and Lopez, 2015). Using a combination of red and blue light (R:B ratio of 1:1) in a multilayer sole-source light propagation system, rather than applying red or blue light alone, reduced stem elongation and enhanced root biomass in herbaceous perennial cuttings. This approach also helps prevent damage during shipping and transplanting (Owen and Lopez, 2019). The architecture of plant shoots, specifically stem elongation, can be managed by controlling shade avoidance. This phenomenon is linked to excessive plant growth under shade or high-density conditions, where photosynthetically active radiation (PAR) availability decreases, along with the R/Fr light ratio (Ruberti *et al*., 2012). Physiological changes, along with a low phytochrome stationary state, promote internode and petiole elongation, axillary bud outgrowth, and hyponasty (Ruberti *et al*., 2012). Cut chrysanthemum flowers in the global market are expected to have an elongated, unbranched plant shape with large-sized flowers. Treating rooted chrysanthemum cuttings with a mix of blue and far-red light led to increased internode length compared to using only red light; in decapitated cuttings, the apical bud reached a high length while growth of underlying buds was inhibited (Dierck *et al*., 2017). In lilium, used as a cut flower, varying red to blue light ratios impact different characteristics; exposure to a high red percentage (R:B ratio of 80:20) significantly enhances stem height (Flores-Pérez *et al*., 2021). Increasing the blue light percentage influenced various morphological traits, including reduced time to harvest (R:B ratio of 20:80), strong inhibition of stem elongation (R:B ratio of 40:60), and slightly improved vase life (R:B ratio of 60:40) (Flores-Pérez *et al*., 2021). Potted miniature rose 'Aga' plants, when exposed to a wide spectrum of red, blue, white, and FR LEDs, showed increased height and shoot length compared to control plants (Matysiak, 2021).

9. Flower and Leaf Color

In addition to plant architecture and longevity, the color of the leaves and flowers is a crucial quality index for the ornamental plant industry as it helps consumers determine their preferences and, consequently, their purchases. The primary groups of plant pigments that control the color of leaves and flowers are battalions, flavonoids, anthocyanins, carotenoids, and chlorophylls (Zhao and Tao, 2015). The variegation of leaf color can be impacted by environmental factors such as temperature, light intensity, and quality (Tilney-Bassett, 1986). Notably, higher light intensities are essential for the expression of pigmentation in leaves, particularly for anthocyanin and carotenoid pigments (Kim *et al*., 2012). In regions with limited light intensity, such as northern greenhouse production areas, achieving high-quality foliage plants may be challenging. Growers in these areas often face difficulties during the winter with insufficient light intensity, leading to inadequate pigmentation in foliage plants and reduced attractiveness and value. While the use of high-pressure sodium (HPS) lamps is currently the primary method to enhance leaf coloration, it also escalates energy and production expenses. When grown in full sun, the flowers of boronia and tuberose plants develop a deep reddish-purple coloration, in contrast to flowers grown in partial shade (Lee *et al*., 2007). Moreover, it has been documented that pigment accumulation in different plant organs can be modulated by light. For example, the exposure of *Hibiscus syriacus* L. flowers to red light influenced the development of a strong red color in their petals (Young *et al*., 1997). During winter, the low light intensity negatively affects the visual appeal of certain potted foliage plants as it hinders the full synthesis of pigments. However, the use of LED supplemental lighting, specifically enriched with red and blue wavelengths, has been found to enhance the accumulation of anthocyanins and carotenoids. This results in a more vivid foliage color and an overall enhancement in the plant's decorative value (De Keyser *et al*., 2019). In the case of geraniums and purple fountain grass plants, the supplementation of red and blue LED light towards the end of production significantly elevated the saturation of red color, measured by the chroma index. As a result, this not only improved the aesthetic appeal and quality but also increased the market value of these plants (Owen and Lopez, 2019).

10. Conclusions

Artificial lighting enhances the potential for year-round production of ornamental plants, leading to increased income for growers in the ornamental industry. The precise choice of light spectrum components through LED lighting technology can greatly enhance the quality attributes of ornamental products by impacting various physiological and metabolic processes like flowering, branching, rooting, pigment production, and longevity in a vase. The impact of this technology may differ based on the ornamental species, duration of exposure, and wavelengths used; therefore, pinpointing the ideal light recipes is crucial for optimal outcomes. Controlling flowering can cut down expenses and production duration, ensuring a consistent yield, sculpting the plant's structure, and highlighting its appealing characteristics. Different approaches such as NI, EOD illumination and photoperiod extension using different LED colors are used for better production of ornamentals. Also, LEDs are a good option to reduce the use of growth retardants and enhance the quality of ornamental plants. The level of secondary metabolites increases with higher levels of blue light. The use of LED lighting in controlled environments can result in the creation of ornamental products with enhanced characteristics, marking a new frontier in applied sciences with research centered on species/cultivar specific light needs. Additionally, its implementation can aid in decreasing the utilization of agricultural resources like energy and soil in a sustainable way.

Conflict of interest

The authors declares no conflict of interest

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