

Chapter 15

Control of Morphology by Manipulating Light Quality and Daily Light Integral Using LEDs

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Abstract In northern latitudes, supplemental lighting is utilized to increase the photosynthetic daily light integral in greenhouses during the winter months, which can fall as low as $1\text{--}5 \text{ mol m}^{-2} \text{ d}^{-1}$. Traditionally, supplemental lighting has been provided by high-intensity discharge (HID) lamps, but light-emitting diode (LED) technologies are now available for many greenhouse applications. The use of LEDs for supplemental lighting can be beneficial because wavelengths of light can be selected for applications such as the control of plant growth, development, morphology, and leaf color. However, delivering these precise wavelengths at moderately low intensities with ambient light already present in the greenhouse may prove ineffective at eliciting desired morphological characteristics. Regardless, LEDs have proven to be a viable option to provide supplemental lighting in the many controlled environments.

Keywords Extension growth • Floriculture crops • Light-emitting diodes • Photomorphogenesis • Phytochrome • Seedling growth • Sole-source lighting • Supplemental lighting

15.1 Introduction

Light-emitting diodes (LEDs) provide a novel approach to greenhouse lighting that has yet to be fully researched (Mitchell et al. 2012; Morrow 2008). To date, little research has been published involving the use of LEDs in greenhouses where plants are also subjected to solar radiation. The use of LEDs in a greenhouse production scenario could involve supplemental, photoperiodic, or photomorphogenic lighting

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for select high-value crops (Mitchell et al. 2012; Morrow 2008). While the quantity (intensity) of light supplied to a plant is often a major focus during greenhouse crop production, the quality of light administered can also influence plant growth, development, and morphology.

15.2 Effects of DLI on Plant Morphology

Daily light integral (DLI) describes the cumulative number of photosynthetically active photons (400–700 nm) received during a 24-h period. Numerous studies have reported that DLI influences plant growth and morphology measured in terms of biomass accumulation, leaf area, branch and flower number, and height. For example, Currey and Lopez (2015) reported that leaf, stem, and root biomass accumulation increased linearly with DLI by 122 %, 118 %, and 211 % for geranium (*Pelargonium ×hortorum*), New Guinea impatiens (*Impatiens hawkeri*), and petunia (*Petunia ×hybrida*) cuttings, respectively, as DLI during propagation increased from ≈ 2 to $13 \text{ mol m}^{-2} \text{ d}^{-1}$. Additionally, as DLI during root development increased, the leaf area ratio and specific leaf area of New Guinea impatiens cuttings decreased by 41 and 34 %, respectively. In a separate study, petunia plants were 6 cm shorter when DLI increased from 6.5 to $13.0 \text{ mol m}^{-2} \text{ d}^{-1}$ (Kaczperski et al. 1991). Faust et al. (2005) observed that the number of lateral shoots in ageratum (*Ageratum houstonianum*) and petunia increased by 7.1 and 7.0 as the DLI increased from 5 to $43 \text{ mol m}^{-2} \text{ d}^{-1}$, respectively.

15.3 Effects of Light Quality on Plant Morphology

Light quality is detected by plants using photoreceptors such as phytochromes, cryptochromes, and ultraviolet light receptors (Runkle and Heins 2001). The detection of these wavelengths by the plant can elicit a wide variety of developmental and morphological responses. One of the benefits of utilizing LEDs in a greenhouse setting is the ability to control the spectrum of wavelengths emitted from the arrays to potentially elicit these desired morphological and physiological responses in the plant (Morrow 2008). Specifically, LEDs can be designed to emit wavelengths of light that match the peak absorption of these critical photoreceptors and plant pigments. This not only provides the benefit to manipulate a desired plant response, but it also potentially saves energy by not providing wavelengths of light less or not necessary for production (Mitchell et al. 2012). Additional potential benefits from targeting specific wavelengths of light using LEDs include reduced pest and disease occurrence and increased concentrations of vitamins, minerals, pigments, or phenolic compounds in the plant tissue (Massa et al. 2008). In the next few sections, we will discuss many of these responses to light quality in detail with an emphasis on regulating plant morphology.

15.3.1 Red Light

Red photons of light have a wavelength between 600 and 700 nm. One of the most common roles for red light is to participate in the physiological process of photosynthesis. Specifically, many LED arrays emit red wavelengths at 660 nm, which is very close to the absorption peak of chlorophyll (Massa et al. 2008). Thus, red LEDs can be used to efficiently drive photosynthetic activity, resulting in increased biomass and overall plant productivity. However, red light alone is not sufficient for the optimum production and quality of most crops. When exposed to solely red light, many dicotyledonous crops develop extensive hypocotyl elongation (Hoenecke et al. 1992). Additionally, *Arabidopsis* plants grown under only red light develop abnormal morphological characteristics (Goins et al. 1998). However, both red and blue light (400–500 nm) control stem elongation (Kigel and Cosgrove 1991). Specifically, blue light, when combined at a low irradiance with red light, can prevent excessive elongation of hypocotyls, stems, and petioles and deter other morphological abnormalities observed under solely red wavelengths (Goins et al. 1998; Hoenecke et al. 1992).

Red light is involved in much more than simply photosynthetic activity. Phytochrome is one of the primary families of photoreceptors that absorb red light as well as far-red (700–800 nm) radiation. When exposed to light, phytochromes exist in two interconvertible forms, the red-absorbing (P_r) and far-red-absorbing (P_{fr}) forms (Smith and Whitelam 1990). The relative proportion of P_{fr} to the total amount of phytochrome (phytochrome photoequilibrium) regulates a variety of photomorphogenic responses including stem extension (Runkle and Heins 2001; Stutte 2009) and flowering (see Chap. 14). These photomorphogenic responses are known to vary with plant species and cultivar, age, light quantity and quality, and temperature. Plants are generally more compact when exposed to light with a high red to far-red ratio (R:FR). They are also more sensitive to red and far-red light at the end of the day (EOD), and 10–60 min of EOD red light may be as effective as a high R:FR during the entire photoperiod to inhibit extension growth (Ilias and Rajapakse 2005).

15.3.2 Blue Light

Blue photons of light have a wavelength between 400 and 500 nm and mediate stem extension, thus inhibiting extension growth for a variety of crops (Cosgrove 1981; Kigel and Cosgrove 1991; Runkle and Heins 2001). However, subjecting plants to solely blue wavelengths can result in elongation responses similar to that under monochromatic red light (van Ieperen et al. 2012). Thus, combinations of both red and blue wavelengths are usually necessary to produce compact plants without excessive elongation. For example, supplemental and sole-source lighting combinations of red and blue light from LEDs produce more compact bedding plant

seedlings (Randall and Lopez 2014; Wollaeger and Runkle 2014). Results from studies such as these will be discussed later in this chapter.

Blue light with or without red light can also affect stomatal density and aperture (Kinoshita et al. 2001; van Ieperen et al. 2012; Zeiger et al. 2002). Specifically, when blue light is added in small quantities to red light, stomatal opening increases significantly compared to solely red light (Kinoshita et al. 2001; van Ieperen et al. 2012). This regulation of stomatal opening by blue light is believed to be mediated through the blue light receptors phot1 and phot2. This increase in stomatal opening ultimately leads to increased carbon dioxide (CO₂) uptake, which further stimulates the process of photosynthesis (Kinoshita et al. 2001).

15.3.3 Far-Red Light

Far-red photons have a wavelength from 700 to 800 nm and thus, by definition, are outside the photosynthetically active radiation (PAR, 400–700 nm) wave band. Thus, the utility of far-red light has predominately been connected to flowering and morphological responses for greenhouse production. One such manipulation involves the phytochrome photoequilibrium, which can be manipulated using LEDs to either initiate earlier flowering in some long-day plants or promote continued growth in the vegetative state (Downs and Thomas 1982; Stutte 2009). A deficiency in far red can delay flower initiation or development in select plants with a long-day photoperiodic response (Runkle and Heins 2001). Thus, a lack of ample far-red light in a production environment may lead to a delay in flowering for some species.

15.4 Supplemental Lighting

The DLI measured inside a greenhouse is often 40–50 % lower than outside due to reflection and absorption of photons by the greenhouse infrastructure and glazing (Hanan 1998). Shading materials and energy curtains, which are used to manage temperature during periods of high solar radiation and low outdoor temperature, respectively, can further reduce the DLI by 40–80 % (Faust et al. 2005). Therefore, supplemental lighting is primarily utilized in commercial greenhouses located in temperate latitudes during the darker months of the year, when solar radiation limits production. For example, more than 2150 ha of glasshouses in the Netherlands use supplemental lighting for ornamental and vegetable propagation and production (Heuvelink et al. 2006). Additionally, supplemental lighting enables producers to meet consumer demand for local and year-round production of specialty crops including fruits, vegetables, and ornamentals.

High-intensity discharge lamps, especially high-pressure sodium (HPS) lamps, have been traditionally used for supplemental lighting in commercial greenhouses

to increase photosynthesis. High-pressure sodium lamps are the most widely used lamp type because of their relatively high efficacy (conversion of electricity into photosynthetic light) and lifespan of 10,000–12,000 h. However, approximately 70 % of energy consumed by the fixtures is not converted into PAR and, instead, is emitted as radiant heat energy. The surface temperature of HPS lamps can reach as high as 450 °C, which requires the separation of lamps from plants (Fisher and Both 2004; Nelson 2012; Spaargaren 2001). Additionally, HPS lamps primarily emit light in the range of 565–700 nm, which is predominately yellow (565–590 nm) and orange (590–625 nm) light. They only emit 5 % blue light, which is low compared to solar radiation that contains 18 % blue light (Islam et al. 2012).

15.4.1 LED Supplemental Lighting for Ornamental Seedling and Cutting Propagation

The production of ornamental young plants, such as seedlings (plugs) and rooted cuttings (liners) (also called transplants), often occurs during winter and early spring (Styer 2003). However, the DLI during this time is at seasonally low levels of 5 mol m⁻² d⁻¹ or less inside many greenhouses located in northern latitudes (Lopez and Runkle 2008; Pramuk and Runkle 2005). This low-average DLI during seedling and cutting propagation can delay rooting and subsequent performance; previous research has shown that a target DLI of 10–12 mol m⁻² d⁻¹ is recommended to produce high-quality young plants (Pramuk and Runkle 2005; Randall and Lopez 2014). Generally, increases in DLI increase the quality of both plugs and liners. A quality young plant is one that has a compact growth habit without excessively large leaves, a high root and shoot mass, a well-developed root system, and a thick stem (Oh et al. 2010; Pramuk and Runkle 2005; Randall and Lopez 2015). These qualitative parameters ultimately lead to seedlings and rooted cuttings that are more easily processed, shipped, and mechanically transplanted, which are desired by growers (Pramuk and Runkle 2005). These higher-quality young plants are often produced at elevated DLIs, leading to increases in dry mass per unit fresh mass (Faust et al. 2005). This results in thicker tissues that contain more carbohydrates and structural materials for use in growth and development. In contrast, young plants grown under a low DLI possess more water in their tissues, resulting in softer tissues that growers refer to as being less “toned” (Faust et al. 2005).

Providing supplemental lighting is a means by which young plants can be grown under a favorable DLI for uniform and consistent production, quality, and subsequent performance (Hernández and Kubota 2012). Currently, HPS lamps are the industry standard for providing supplemental lighting and commonly deliver a photosynthetic photon flux (PPF) of 50–80 μmol m⁻² s⁻¹ for most crops (Fisher and Both 2004). Although high-intensity LED arrays for greenhouse supplemental lighting are still a relatively new technology, they have the potential to offer

greater efficiencies, longer lifetimes, and wavelength specificity for young plant production.

Young plants grown under LED supplemental lighting are typically of equal or higher quality to those grown under HPS lamps. Specifically, Randall and Lopez (2014) placed seedlings of celosia (*Celosia argentea*), geranium, impatiens (*Impatiens walleriana*), marigold (*Tagetes patula*), pansy (*Viola × wittrockiana*), petunia, salvia (*Salvia splendens*), snapdragon (*Antirrhinum majus*), and vinca (*Catharanthus roseus*) under a 16-h photoperiod of solar radiation plus supplemental lighting providing a PPF of $100 \mu\text{mol m}^{-2} \text{s}^{-1}$ from either HPS lamps or LED arrays with varying proportions (%) of red/blue ratios (100:0, 85:15, or 70:30). Seedlings of some species grown under red+blue LEDs were generally more compact, had a greater stem diameter and relative chlorophyll content, and possessed a higher quality index [a quantitative measurement of quality (Currey et al. 2013)] than those under HPS lamps or only red LEDs. For example, stem extension of celosia, impatiens, marigold, pansy, petunia, salvia, and vinca was suppressed by 29 %, 31 %, 20 %, 35 %, 55 %, 9 %, and 31 %, respectively, for seedlings grown for 28 days under 85:15 red/blue LEDs compared with those grown under HPS lamps (Fig. 15.1). Additionally, stem diameter of geranium, marigold, and snapdragon was 8 %, 13 %, and 18 % greater, respectively, for seedlings grown under the 85:15 red/blue LEDs compared with seedlings grown under HPS lamps. However, root and shoot dry mass were similar between seedlings of the same three species and vinca grown under LED and HPS supplemental lighting. Overall, the quality index was similar for geranium, impatiens, marigold, snapdragon, and vinca grown under LEDs and HPS lamps. In contrast, Randall and Lopez (2014) reported that the quality index was higher for pansy, petunia, and salvia under 100:0, 85:15, and 70:30 red/blue LEDs than under HPS lamps.

In a separate study, Randall and Lopez (2015) compared seedlings grown under a low ambient greenhouse DLI of $\approx 6 \text{ mol m}^{-2} \text{ d}^{-1}$ with those grown under supplemental lighting or with sole-source lighting in a growth chamber with a DLI of $\approx 11 \text{ mol m}^{-2} \text{ d}^{-1}$. The researchers placed marigold, geranium, impatiens, petunia, and vinca under ambient solar light for 16 h with supplemental light ($70 \mu\text{mol m}^{-2} \text{ s}^{-1}$) from HPS lamps or LEDs providing 87:13 red/blue light. Seedlings of the same species were also grown under LEDs providing $185 \mu\text{mol m}^{-2} \text{ s}^{-1}$ from either 87:13 or 70:30 red/blue light for 16 h. Root and shoot dry mass, leaf number and area, stem diameter, relative chlorophyll content, and the quality index of most species were generally greater under supplemental and sole-source lighting. Similar to the results of Randall and Lopez (2014), stem extension of all species under the red+blue LED supplemental lighting was less than seedlings grown under HPS lamps. Additionally, stem length of geranium, marigold, and petunia under red+blue LED sole-source lighting was suppressed by 21–26 %, 16–18 %, and 75–79 %, respectively, than seedlings grown under HPS supplemental lighting. Interestingly, leaf area of geranium was 49 %, 20 %, and 24 % greater for seedlings grown under HPS lamps compared with those under ambient solar radiation and sole-source LEDs providing 87:13 and 70:30 red/blue light, respectively (Fig. 15.2).

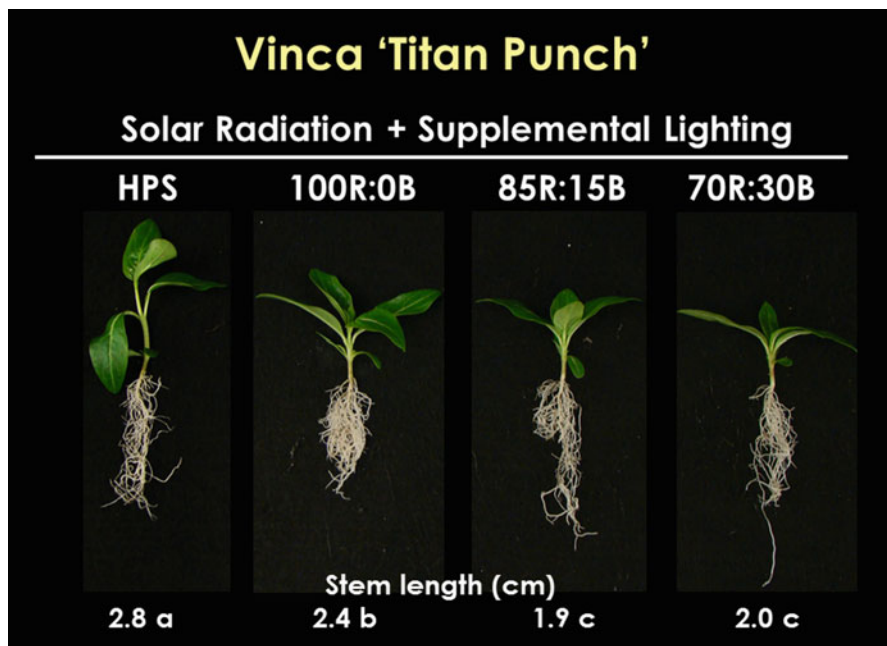


Fig. 15.1 *Vinca* seedlings grown in a greenhouse at 23 °C for 28 days under ambient solar radiation supplemented with $100 \mu\text{mol m}^{-2} \text{s}^{-1}$ from high-pressure sodium (HPS) lamps or light-emitting diodes (LEDs) with varying red/blue (R/B) light ratios (100:0, 85:15, or 70:30) (Randall and Lopez 2014). Means sharing a letter are not statistically different by Tukey's honestly significant difference at $P \leq 0.05$

Compared to seedlings, Currey and Lopez (2013) observed little effect of supplemental light source during cutting propagation on growth, morphology, and subsequent flowering after transplant. In this study, cuttings of New Guinea impatiens, zonal geranium, and petunia were grown for 7 days under a low DLI of $\approx 5 \text{ mol m}^{-2} \text{ d}^{-1}$ for callusing. Cuttings were placed under natural days and supplemental lighting as needed to deliver a 16-h photoperiod at $70 \mu\text{mol m}^{-2} \text{ s}^{-1}$ from either HPS lamps or LED arrays with red/blue ratios of 100:0, 85:15, or 70:30. The only significant effects observed were that stem length of petunia was shortest for cuttings propagated under 100:0 red/blue LEDs, and leaf and root dry mass of petunia propagated under 70:30 red/blue LEDs were greater than cuttings propagated under HPS lights (Fig. 15.3). However, these differences were not commercially significant for growers. Additionally, supplemental light source during propagation had little or no effect on subsequent flowering of finished plants, including time to flower, stem length, node number below the first flower or inflorescence, flower bud number, and shoot dry mass.

For supplemental lighting in the greenhouse, it is plausible that the spectral quality has little potential to elicit morphological effects given the abundant background radiation provided by natural sunlight. This observation has been

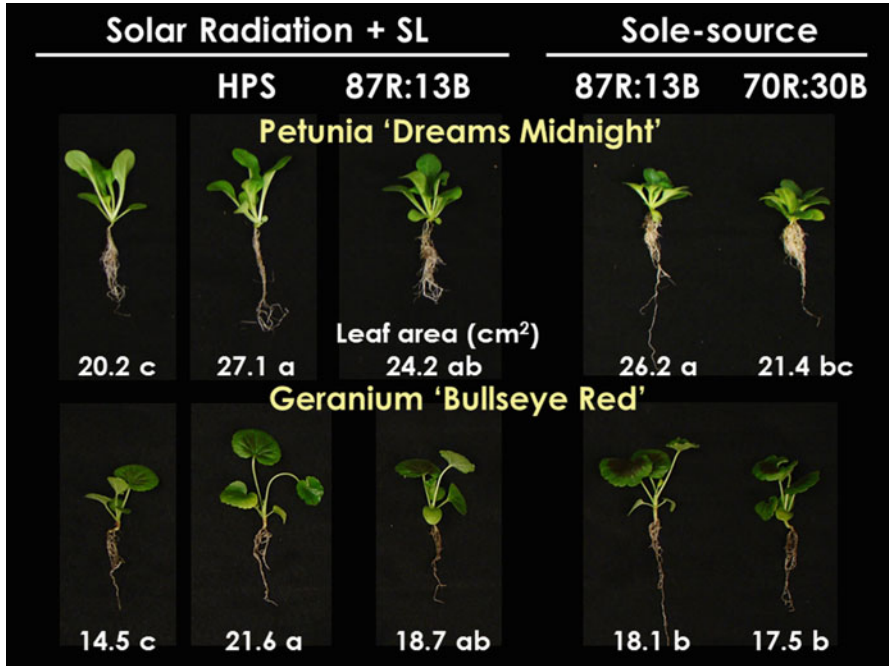


Fig. 15.2 Petunia and geranium seedlings grown at 23 °C for 21 days under ambient greenhouse solar radiation without or with 70 $\mu\text{mol m}^{-2} \text{s}^{-1}$ from high-pressure sodium (HPS) lamps or light-emitting diodes (LEDs) for 16 h with an 87:13 red/blue (R:B) light ratio or under 185 $\mu\text{mol m}^{-2} \text{s}^{-1}$ of sole-source lighting from LEDs for 16 h with a R/B light ratio of 87:13 or 70:30 (Randall and Lopez 2015). Means sharing a letter are not statistically different by Tukey's honestly significant difference at $P \leq 0.05$

suggested by Hernández and Kubota (2012) when they found that supplemental blue light administered to tomato (*Solanum lycopersicum* 'Komeett') seedlings at red/blue ratios of 96:4 and 84:16 at an intensity of 55 $\mu\text{mol m}^{-2} \text{s}^{-1}$ elicited no change to seedling growth, morphology, or photosynthesis. They suggested that supplemental red light is sufficient for the production of tomato seedlings due to the solar background radiation providing sufficient quantities of blue light. Thus, light quality provided to vegetable seedlings may not be as important as reaching the minimum DLI for optimum production.

In addition to supplemental lighting, sole-source lighting with LEDs has become an alternative for seedling production. The commercial production viability of using LEDs in sole-source lighting is related to their low output of radiant heat, allowing the arrays to be placed close to the crop canopy to maximize production space efficiency. As discussed previously, Randall and Lopez (2015) evaluated various popular bedding plant seedlings under sole-source lighting using LEDs providing a red/blue light ratio of either 87:13 or 70:30 at 185 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Generally, seedlings produced under sole-source lighting were more compact (reduced height and leaf area), darker in foliage color (higher relative chlorophyll

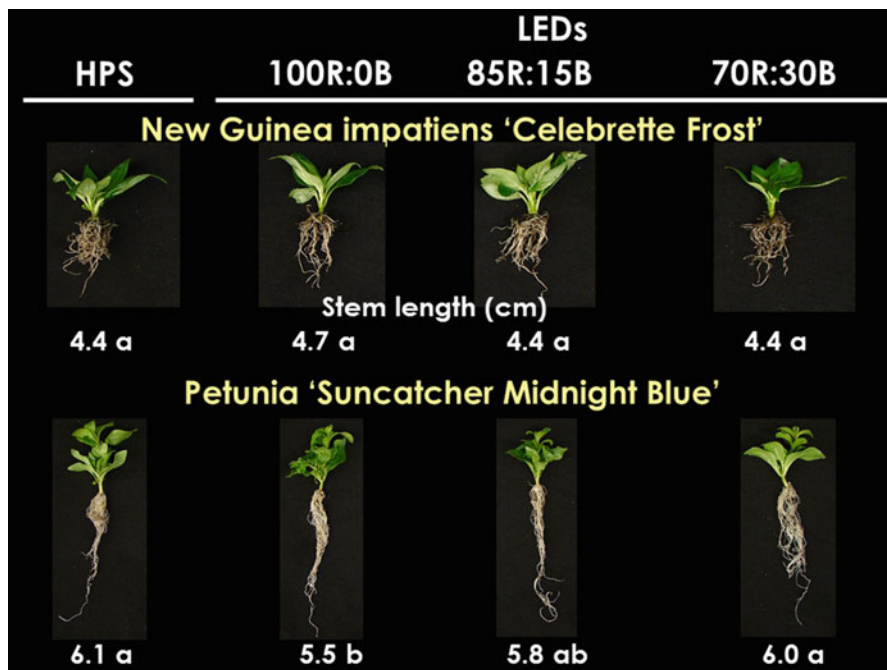


Fig. 15.3 New Guinea impatiens and petunia cuttings propagated for 14 days at 23 °C under ambient greenhouse solar radiation supplemented with 70 $\mu\text{mol m}^{-2} \text{s}^{-1}$ from high-pressure sodium (HPS) lamps or light-emitting diodes (LEDs) for 16 h with red/blue (R/B) light ratios of 100:0, 85:15, or 70:30 (Currey and Lopez 2013). Means sharing a letter are not statistically different by Tukey's honestly significant difference at $P \leq 0.05$

content), and had a higher root mass than those produced under supplemental lighting from HPS lamps or ambient lighting conditions in the greenhouse. Additionally, Wollaeger and Runkle (2014) reported that compact bedding plant seedlings could be produced under LED sole-source lighting providing red and blue and/or green wavelengths of light (Fig. 15.4). Ultimately, they believe that this production method may eliminate the need for plant growth regulator applications to inhibit extension growth because height can be manipulated through lighting. Thus, while the effects of light quality may be diminished from background ambient sunlight during supplemental lighting applications in the greenhouse, sole-source lighting enables growers to manipulate light quality to elicit desired morphological and physiological attributes.

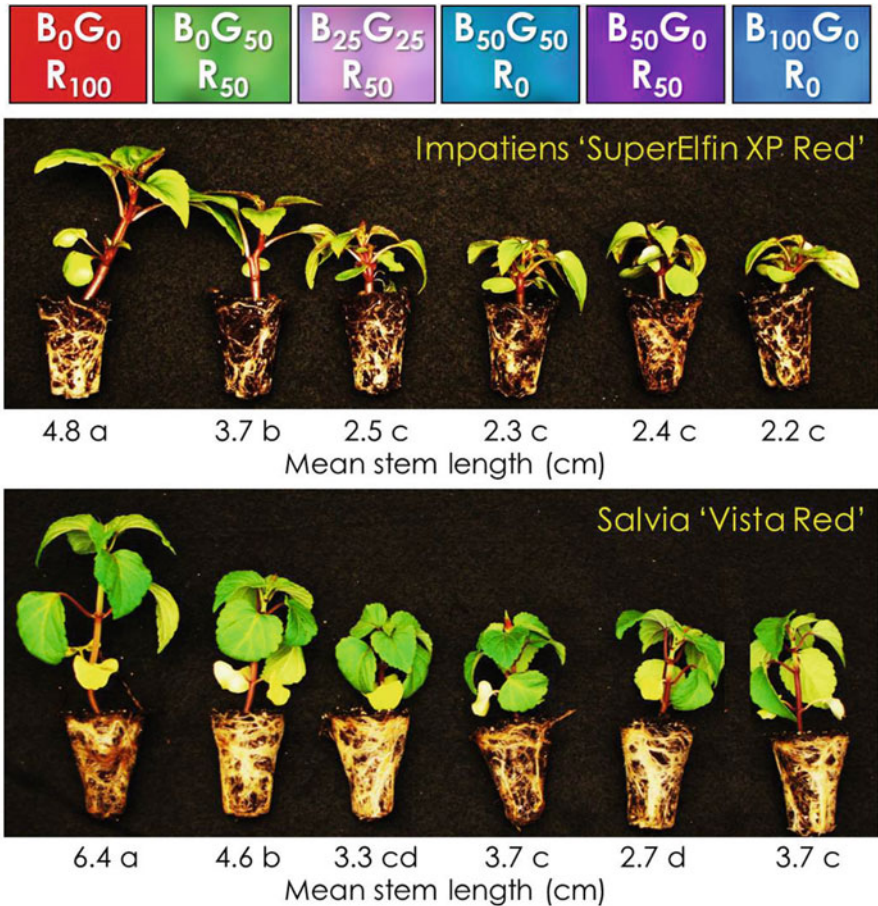


Fig. 15.4 Seedlings of impatiens or salvia grown for 4 weeks at 20 °C under sole-source LED lighting treatments that each delivered a PPF of $160 \mu\text{mol m}^{-2} \text{s}^{-1}$ for $18 \text{ h}\cdot\text{d}^{-1}$ (Wollaeger and Runkle 2014). Peak wavelengths: blue (B), 446 nm; green (G), 516 nm; red (R), 634 nm + 664 nm. Means sharing a letter are not statistically different by Tukey's honestly significant difference at $P \leq 0.05$

15.4.2 LED Supplemental Light for Ornamental Crop Finishing

Manipulation of morphology, flowering, and foliage color is important in the greenhouse production of high-quality potted and bedding plants. Light-emitting diodes can be used to manipulate plant morphology and foliage color by delivering specific wave bands of light. For example, Islam et al. (2012) conducted a study to determine whether supplemental lighting from LEDs providing an increased amount of blue light influenced the growth and morphology of poinsettia (*Euphorbia pulcherrima*).

They placed poinsettia ‘Christmas Spirit’, ‘Christmas Eve’, and ‘Advent Red’, under a 10-h photoperiod of solar radiation plus supplemental lighting providing a PPF of $100 \mu\text{mol m}^{-2} \text{s}^{-1}$ from either HPS lamps emitting 5% blue light or LED arrays emitting a red/blue light ratio of 80:20. The estimated phytochrome photoequilibrium state was 0.85 and 0.89 for the HPS and LEDs, respectively. After 12 weeks, stem, internode, and petiole length; bract area; leaf area; and total dry mass of all cultivars were reduced (by 17–61%) when grown under the R + B LEDs compared to HPS lamps.

In a separate study, 8–10-day-old petunia ‘Tidal Wave’ seedlings were placed under frames covered with either a far-red absorbing film (–FR) or two layers of clear polyethylene plastic film (+FR) in a greenhouse (Gautam et al. 2015). Light-emitting diode arrays with a red/blue light ratio of 50:50 were placed underneath the films and provided a PPF of $50 \mu\text{mol m}^{-2} \text{s}^{-1}$. Additionally, one treatment only contained HPS lamps above the films to provide a PPF of $180 \mu\text{mol m}^{-2} \text{s}^{-1}$ for 16 h. High-pressure sodium lamps were placed above the LED treatments and provided an additional PPF of $100 \mu\text{mol m}^{-2} \text{s}^{-1}$ for 16 h. Under a lower natural irradiance in the spring, petunia shoots were 25% shorter if they were grown under supplemental lighting from red LEDs compared to plants under the +FR and –FR treatments receiving supplemental light from HPS lamps or blue LEDs. Additionally, under the low natural irradiance, and especially in the presence of FR light, blue light promoted flowering of petunia, but increased shoot elongation and plant height.

Growers sometimes observe that ornamental foliage is not as colorful (e.g., a pale red/purple) during the winter and early spring due to low-light greenhouse conditions. Owen and Lopez (2015a) determined whether a short exposure to end-of-production supplemental lighting from different sources and intensities would influence foliage color. They placed geranium ‘Black Velvet’ and purple fountain grass (*Pennisetum setaceum* ‘Rubrum’) plants under a 16-h photoperiod consisting of ambient solar radiation plus day-extension light at $4.5 \mu\text{mol m}^{-2} \text{s}^{-1}$ from LEDs, $70 \mu\text{mol m}^{-2} \text{s}^{-1}$ from HPS lamps, or one of six LED arrays. The six LED arrays were $100 \mu\text{mol m}^{-2} \text{s}^{-1}$ of monochromatic red; 25, 50, or $100 \mu\text{mol m}^{-2} \text{s}^{-1}$ of monochromatic blue; or $100 \mu\text{mol m}^{-2} \text{s}^{-1}$ of 87:13 or 50:50 red/blue light. The supplemental light providing $100 \mu\text{mol m}^{-2} \text{s}^{-1}$ of 0:100 red/blue light enhanced pigmentation of geranium and purple fountain grass leaves the most when plants were grown under a greenhouse DLI of $<9 \text{ mol m}^{-2} \text{d}^{-1}$. For example, purple fountain grass placed under the control or $100 \mu\text{mol m}^{-2} \text{s}^{-1}$ of 100:0, 0:100, 50:50, or 87:13 red/blue supplemental light had hue angle (h°) values of 91° , 57° , 4° , 44° , and 70° , respectively. Therefore, foliage color of plants under blue LEDs at $100 \mu\text{mol m}^{-2} \text{s}^{-1}$ were the darkest red because the h° was the lowest.

15.4.3 LED Supplemental Light for Vegetable Production

During the winter months, supplemental lighting for greenhouse vegetable crop production is becoming more commonplace for many species (Chap. 16). Much of

the research conducted regarding LED supplemental lighting for vegetable production has naturally focused on how to impact factors such as yield and marketability for a variety of crops (Deram et al. 2014; Gómez et al. 2013; Trouwborst et al. 2010). Light-emitting diodes can also be used for a few days or weeks prior to harvest to elicit specific morphological or physiological effects, such as to increase coloration on lettuce (*Lactuca sativa*) varieties to increase the marketability and quality of the crop. Providing lettuce varieties ‘Cherokee’, ‘Magenta’, ‘Ruby Sky’, and ‘Vulcan’ with LED red/blue light ratios of 100:0, 50:50, or 0:100 at $100 \mu\text{mol m}^{-2} \text{s}^{-1}$ with a 16-h photoperiod produced darker red foliage compared to those grown under HPS lamps, lower intensities of the same ratios, or no supplemental lighting (Owen and Lopez 2015b; Fig. 15.5). With as little as 5–7 days of supplemental lighting prior to harvest, anthocyanin synthesis and thus pigmentation increased in these lettuce crops. Anthocyanins are a plant pigment involved in the red coloration of plant foliage and have a variety of human health-promoting benefits. Earlier research by Li and Kubota (2009) reported that supplemental blue or UV-A light could be utilized to increase the accumulation of this plant pigment in baby leaf lettuce ‘Red Cross’. Thus, the utilization of LEDs for supplemental lighting of lettuce crops has the potential to improve aesthetic quality and nutritional value.

Supplemental lighting provided by red-orange and blue LEDs can significantly inhibit hypocotyl elongation of lettuce seedlings during the early stages of plant growth compared to under HPS lamps (Pinho et al. 2007). This inhibition of elongation was attributed to the 20 % of blue light included in the LEDs. Similarly, the inclusion of blue light in intracanopy supplemental lighting reduced the length of internodes for both tomato and cucumber (*Cucumis sativus*) (Ménard et al. 2006). An increase in the red/far-red ratio also reduced internode length and increased fruit coloration for these species (Ménard et al. 2006). Thus, by manipulating the wavelengths of light provided, the production of many crops can be enhanced by controlling excessive growth and elongation. However, results were obtained using intracanopy supplemental lighting, where ambient light is significantly reduced due to the developing canopy. Therefore, while supplemental light quality effects are negligible at times because of the background radiation, as discussed previously, the manipulation of plant morphology through light quality is more plausible using intracanopy supplemental lighting.

15.5 Concluding Summary

Light-emitting diodes provide an alternative to traditional greenhouse lighting sources for many supplemental lighting applications. While the benefit of targeting specific wavelengths of light may be negligible against ambient light, the relatively high energy efficiency and long lifespan of most LEDs remain desirable attributes. Additionally, with applications such as intracanopy, end of production, and sole-source lighting becoming increasingly popular, the utilization of wavelength

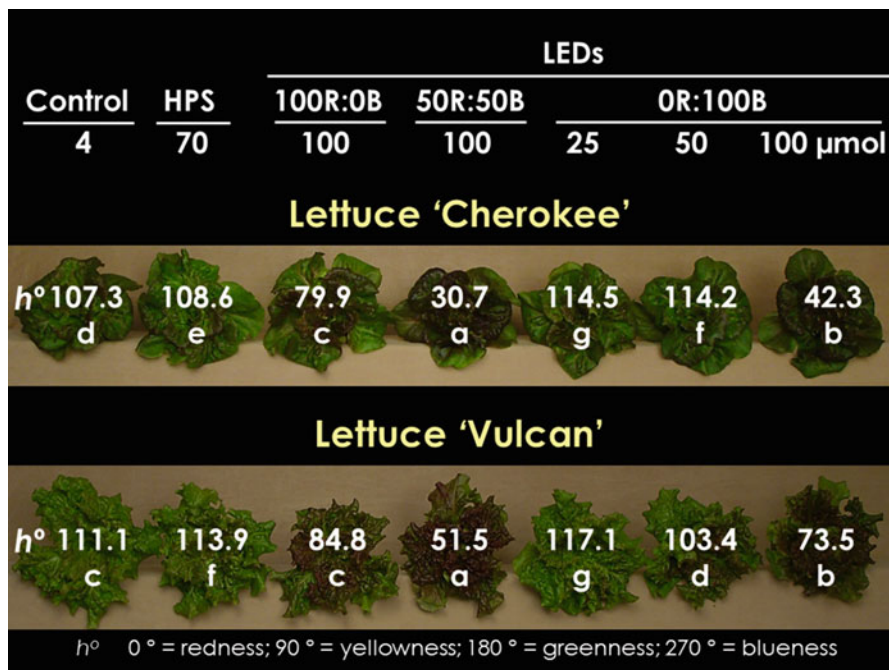


Fig. 15.5 Average hue angle (h°) of lettuce grown in a greenhouse at 18 °C and then provided with 7 days of day-extension lighting to deliver a 16-h photoperiod from low-intensity light-emitting diode (LED) lamps or 16 h of supplemental light from high-pressure sodium (HPS) lamps or LED arrays with different red/blue ratios (R:B). Values under each lighting treatment indicate the PPF in $\mu\text{mol m}^{-2} \text{s}^{-1}$. Within-row h° means followed by different letters are significantly different (Owen and Lopez 2015 b)

specificity provided by LEDs will only increase as their manufacturing costs continue to decrease while their electrical efficacy continues to increase.

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