Geranium and Purple Fountain Grass Leaf Pigmentation Is Influenced by End-of-Production Supplemental Lighting with Red and Blue Light-emitting Diodes

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Abstract. Under low-light greenhouse conditions, anthocyanin pigmentation in vegetative tissues of red- or purple-leaved floricultural crops is not fully expressed and, consequently, plants are not as visually appealing to consumers. Our objective was to quantify the effect of end-of-production (EOP; before shipping) supplemental lighting (SL) of different light sources, qualities, and intensities on foliage color of geranium (Pelargonium × hortorum) and purple fountain grass (Pennisetum × advena). Plants were finished under early (Expt. 1) and late (Expt. 2) seasonal greenhouse ambient solar light and provided with 16 hours of day-extension lighting from low-intensity light-emitting diode (LED) lamps [7:11:33:49 blue:green:red:far-red light ratio (%); control] delivering 4.5 μmol·m–2·s–1, or 16 hours of EOP SL from high-pressure sodium (HPS) lamps delivering 70 μmol·m–2·s–1, or LED arrays (100:0, 87:13, 50:50, or 0:100 red:blue) delivering 100 μmol·m–2·s–1, or 0:100 red:blue LEDs delivering 25 or 50 μmol·m–2·s–1. Geranium and fountain grass chlorophyll content and leaf color were estimated using a SPAD-502 chlorophyll meter and Minolta ‘Rubrum’); plants were grown under a low greenhouse DLI (8.6 mol·L–1 of 100:0, 87:13, 50:50, or 0:100 red:blue; delivering 4.5 μmol·m–2·s–1, or 16 hours of EOP SL from high-pressure sodium (HPS) lamps delivering 70 μmol·m–2·s–1, or LED arrays (100:0, 87:13, 50:50, or 0:100 red:blue) delivering 100 μmol·m–2·s–1, or 0:100 red:blue LEDs delivering 25 or 50 μmol·m–2·s–1. Geranium and fountain grass chlorophyll content and leaf color were estimated using a SPAD-502 chlorophyll meter and Minolta tristimulus colorimeter, respectively. Relative chlorophyll content (RCC) and foliage hue (L*, C* (chroma; a measure of saturation), and h° (hue angle; a measure of tone) values were significantly influenced by EOP SL and days of exposure. Generally, RCC of geranium and fountain grass increased from 3 to 14 days of exposure to EOP SL from HPS lamps and LEDs delivering 100 μmol·m–2·s–1. Under low daily light integrals (DLIs) [8.6 mol·m–2·d–1 (geranium) and 9.4 mol·m–2·d–1 (purple fountain grass)] EOP SL providing 100 μmol·m–2·s–1 of 100:0, 87:13, 50:50, or 0:100 red:blue light for ≥14 days resulted in lower L* (darker foliage), C* (saturated), and h° (orange to violet-rect hues). Our data indicate that a minimum of 14 days of EOP SL providing 100 μmol·m–2·s–1 of 50:50 or 0:100 red:blue light enhanced foliage color of geranium and fountain grass leaves when plants were grown under a low greenhouse DLI ≤ 9 mol·m–2·d–1.

In floriculture crops, aesthetic qualities, including flower and foliage color or variegation, influence consumers’ initial perceptions.

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use of LEDs to enhance foliage color and the aesthetic quality of floricultur crops. Recently, Owen and Lopez (2015) found 5 to 7 d of EOP (before harvest) SL from LEDs providing 100 μmol·m⁻²·s⁻¹ of 100:0, 50:50, or 0:10 red:blue light for 16-h increased foliage color of four varieties of red leaf lettuce (Lactuca sativa L. ‘Cherokee’, ‘Magenta’, ‘Ruby Sky’, and ‘Vulcan’). Therefore, short-term exposure of monochromatic or combinations of narrow spectrum SL from LEDs is a potential lighting application for bedding plant producers to enhance aesthetic qualities such as leaf color. To our knowledge, no published information exists on EOP (before shipping) SL from LEDs to enhance leaf color of greenhouse-grown geranium ‘Black Velvet’ or purple fountain grass. Therefore, the objective of this study was to quantify and compare the effects of EOP SL from HPS lamps to LEDs of different light intensities, light qualities, and days of exposure on the leaf color of two bedding plant species. The two species were chosen based on grower challenges during early spring to produce aesthetically appealing plants with vivid foliage color. In addition, they were selected based on foliage color and leaf morphologies. For geranium ‘Black Velvet’, leaves are reniform and vary from almost “zoned” to completely solid red to dark maroon centers with a contrasting green leaf margin, whereas purple fountain grass leaves are narrow, curving, linear blades that vary in color from dark to vivid red-purple. Therefore, foliage color is imperative for the aesthetic appeal and marketing of both bedding plants.

Materials and Methods

Plant material, culture, and propagation environment. On 25 Jan. (Expt. 1) and 26 Feb. 2014 (Expt. 2), seeds of geranium (Pelargonium ×hortorum ‘Black Velvet’) (American Takii Inc., Salinas, CA) were sown into 72-cell plug trays (30.7-mL individual cell volume; Landmark Plastics, Akron, OH) filled with a commercial soilless medium composed of (by volume) 65% peat, 20% vermiculite, and 15% vermiculite (Super Fine Germinating Mix; Sun Gro Horticulture, Agawam, MA). Seedlings were irrigated with acidified water supplemented with watersoluble fertilizer (Jack’s LX 16N–0.94P–9.4K–0.82 Ca–0.78 Mg–0.55 Fe–0.50 Mn–0.25 Zn–0.25 boron (B; 0.10), copper (Cu; 0.05), and molybdenum (Mo; 0.05)). Irrigation water was supplemented with 93% sulfuric acid (Brenntag, Reading, PA) at 0.08 ppm to reduce alkalinity to 100 mg·L⁻¹ carbonate and pH to a range of 5.8 to 6.2.

Seedlings were grown in a glass-glazed greenhouse at Purdue University, West Lafayette, IN (lat. 40°N) with exhaust fan and evaporative-pad cooling, radiant hot water heating, and retractable shade curtains controlled by an environmental control system (Maximizer Precision 10; Priva Computers Inc., Vineland Station, ON, Canada). Amplified quantum sensors (SQ-212; Aggee Instruments, Inc., Logan, UT) measured PPF every 15 s and the average of each sensor was logged every 15 min by a data logger (WD 2800; Spectrum Technologies, Aurora, IL). Air temperature was monitored and recorded by a separate aspirated Priva sensor (Maximizer Precision 10; Priva Computers Inc.). The greenhouse air temperature set point for Expts. 1 and 2 was a constant 20°C, with a 6-h photoperiod (0600 to 2200 HR) consisting of natural day-lengths with day-extension lighting from HPS lamps (e-system HID; PARSource, Petaluma, CA) that delivered a supplemental PPF of ≈70 μmol·m⁻²·s⁻¹ at plant height. During plug culture, average daily temperature (ADT) and DLI for Expts. 1 and 2 were 19.3 ± 1.8 and 19.4 ± 2.0°C and 11.3 ± 1.1 and 11.3 ± 0.9 mol·m⁻²·d⁻¹, respectively.

On 19 Feb. (Expt. 1) and 23 Mar. (Expt. 2), geranium seedlings were transplanted into 15.2-cm (1.3-L) diameter containers (Dillen Plastics, Middleton, OH). On 6 Feb. (Expt. 1) and 14 Mar. (Expt. 2), 50-deep cell plug trays (106.5-mL individual cell volume; East Jordan Plastics, East Jordan, MI) of purple fountain grass [Pennisetum advena (formerly known as P. setaceum ‘Rubrum’)] were received from a commercial greenhouse supplier (Pleasant View Gardens, Loudon, NH) and transplanted into 12.7-cm (88.5-mL) diameter containers (ITML Horticultural Products, Middleton, OH). Containers were filled with a commercial soilless medium composed of (by volume) 65% peat, 20% perlite, and 15% vermiculite (Super Fine Germinating Mix; Sun Gro Horticulture, Agawam, MA). Seedlings were irrigated with acidified water supplemented with a combination of two water-soluble fertilizers [3:1 mixture of 15N–2.2P–12.5K and 21N–2.2P–16.6K, respectively (Evarris, Marysville, OH)] to provide the following (mg·L⁻¹): N (200), P (26), K (163), Ca (50), Mg (20), Fe (1.0), Mn (0.5), Zn (0.5), Cu (0.24), B (0.24), and Mo (0.1).

Geranium and fountain grass plants were grown under 50% shade cloth (DeWitt Company, Sikesston, MO) to simulate a low-ambient DLI (<10 mol·m⁻²·d⁻¹). The ADT and DLI for geranium culture during Expts. 1 and 2 were 20.7 ± 2.5 and 21.2 ± 2.4°C and 6.0 ± 2.8 and 7.5 ± 4.4 mol·m⁻²·d⁻¹, respectively. The ADT and DLI for fountain grass culture during Expts. 1 and 2 were 20.4 ± 2.7 and 21.2 ± 2.7°C and 6.0 ± 2.7 and 7.2 ± 4.2 mol·m⁻²·d⁻¹, respectively.

EOP greenhouse environment and SL treatments. On 1 Apr. (Expt. 1) and 24 Apr. (Expt. 2), geranium and fountain grass plants were moved to a glass-glazed greenhouse where the air temperature set point was a constant 22°C. Ten plants of each species were placed under a 16-h photoperiod consisting of either ambient solar light plus day-extension light (control; no EOP SL) or EOP SL from 0600 to 2200 HR. Day-extension lighting consisted of two low-intensity LED lamps (7:11:33:49 red:blue:red:blue; Philips GreenPower Flowering deep red/white:far-red LED lamp; Koninklijke Philips Electronics N.V., The Netherlands). Supplemental light was delivered from a 150-W HPS lamp (PL 2000; P.L. Light Systems Inc., Beavinsville, ON, Canada) or one of six LED arrays (Orbital Technologies Corporation, Madison, WI; Koninklijke Philips Electronics N.V.) providing monochromatic red [100:0 red (660 nm):blue (460 nm)], monochromatic blue [0:100 red (732 nm):blue (460 nm)], or a combination of red and blue (7:13 or 50:50: red:blue) light at high or low intensities (Table 1). Spectral scans of the control and EOP SL treatments were taken at night at the beginning of each replication with a spectroradiometer (BLUE-Wave Miniature Spectrometer; StellarNet, Inc., Tampa, FL). Spectral quality of each light source is provided in Fig. 1. The use of 62% shade cloth (XLS 16-F; Ludwig Svensson, Inc., Charlotte, NC) served as a barrier between each EOP treatment to reduce the likelihood of light pollution. Amplified quantum sensors (SQ-110; Aggee Instruments, Inc.) measured solar PPF every 15 s and the average of each sensor was logged every 15 min by a data logger (WD 2800; Spectrum Technologies, Inc.). For geranium, the ADT and average solar DLI after 14 d during Expts. 1 and 2 were 22.7 ± 1.1 and 22.9 ± 1.3°C and 8.6 ± 5.0 and 12.6 ± 4.7 mol·m⁻²·d⁻¹, respectively. For fountain grass, the ADT and average solar DLI after 21 d during Expts. 1 and 2 were 22.7 ± 1.1 and 22.9 ± 1.3°C and 9.4 ± 4.2 and 11.4 ± 5.0 mol·m⁻²·d⁻¹, respectively. The supplemental DLI for each treatment was calculated and is reported in Table 1.

Data collection. For geranium, at 0, 3, 5, 7, and 14 d after initiating EOP SL, total chlorophyll (a + b) content (i.e., RCC) was estimated using a SPAD chlorophyll meter (SPAD-502; Konica Minolta Sensing, Inc., Osaka, Japan) by measuring two recently matured leaves of each plant under each lighting treatment. For fountain grass, RCC were repeatedly measured on the same two leaves at 0, 3, 5, 7, 14, and 21 d. Using the same two leaves previously mentioned for RCC, leaf color was measured for both species using a portable tristimulus colorimeter (CR-200; Konica Minolta Sensing, Inc.) equipped with a measuring head with a self-contained light source that provided diffuse, uniform light over an 8-mm diameter measuring area. The analyzer was calibrated to a standard white reflective plate (L* = 97.5, a* = –0.40, b* = 1.90) using the Commission Internationale de l’Eclairage (CIE) 1976 (L*a*b*) color coordinates. L* values indicate darkness and lightness (black: L* = 0; white: L* = 100). Chromaticity a* values [ratio between greenness and redness (green: a* = –60; red: a* = +60)] and chromaticity b* values [ratio between blueness and yellowness (blue: b* = –60; yellow: a* = +60)] were determined and used to calculate chroma (C*) and hue angle (h°).
Table 1. Lighting manufacturer, spectral color ratio, photon flux, and supplemental DLI derived from spectral scans taken at night for Expt. 1 (1 Apr. 2014) and Expt. 2 (24 Apr. 2014); structural dimensions, number, spacing, and height from bench level at which lighting treatments were placed above geranium (Pellargonium × Hortorum ‘Black Velvet’) and purple fountain grass (P. × Hortorum ‘advena’).

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**Chroma** is a measure of saturation and was calculated as

\[ C^* = \sqrt{a'^2 + b'^2} \]  

On a circular scale, \( h^* \) or tone, indicates redness (0°), yellowness (90°), greenness (180°), or blueness (270°) and was calculated as

\[ h^* = \tan^{-1}\left(\frac{b^*}{a^*}\right) \]

**Statistical analysis.** All plants for each species in Expts. 1 and 2 were grown under a common greenhouse environment, therefore, average RCC, L*, C*, and \( h^* \) values were similar before initiating EOP SL treatments (0 d). The experiment used a completely randomized design in a factorial arrangement. The factors were EOP SL treatment (eight levels) and days after lighting (four levels for geranium; five levels for fountain grass). Species were not compared. There were 10 plants per species (two individual samples per plant) per EOP SL treatment (20 samples per SL treatment). Interactions among EOP SL and days after lighting were not significant; therefore, main effects were reported. Effects of EOP SL and days after lighting were analyzed using SAS (version 9.2; SAS Institute, Cary, NC) mixed model procedure (PROC MIXED) for analysis of variance and means were separated by Fisher’s least significant differences at \( P \leq 0.05 \). For RCC, data were not statistically different between experiments; therefore, data were pooled for each species.

**Results and Discussion**

Effects of EOP SL and days of exposure on RCC. End-of-production SL and days of exposure significantly influenced RCC of geranium and fountain grass (Table 2). At initiation (0 d), the average RCC of geranium and fountain grass was 48.4 and 35.3, respectively. In general, for geranium, as days of exposure increased, RCC increased for all plants under each EOP SL treatment. For example, from 3 to 14 d of EOP SL delivering 100 μmol·m⁻²·s⁻¹ provided by 100:0, 87:13, 50:50, and 0:100 red: blue light, RCC increased from 48.8 to 62.0, 49.4 to 61.7, 48.5 to 63.1, and 44.6 to 62.2 (Table 2), respectively. Compared with no EOP SL (control), RCC of geranium was significantly higher under LED EOP SL delivering 100 μmol·m⁻²·s⁻¹. Similarly, Owen and Lopez (2015) reported 14 d of EOP SL delivering 100 μmol·m⁻²·s⁻¹ provided by 100:0, 0:100, or 50:50 red:blue light, resulted in increased RCC from 29.6 to 32.8 and 26.5 to 29.0 for lettuce ‘Cherokee’ and ‘Ruby Sky’ plants, respectively, compared with the control.

For fountain grass, regardless of EOP SL source, RCC significantly increased up to 14 d after exposure to EOP SL; however, an additional 7 d (21 d) of exposure to EOP SL resulted in no significant differences (Table 2). For instance, 14 and 21 d of EOP SL resulted in RCC of 38.4 and 38.7,

**Table 2.** Lighting manufacturer, spectral color ratio, photon flux, and supplemental DLI derived from spectral scans taken at night for Expt. 1 (1 Apr. 2014) and Expt. 2 (24 Apr. 2014); structural dimensions, number, spacing, and height from bench level at which lighting treatments were placed above geranium (Pelargonium × Hortorum ‘Black Velvet’) and purple fountain grass (P. × Hortorum ‘advena’).

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Effects of seasonal DLI on foliage color. Average leaf lightness (L*) and chroma (C*) values and hue angle (h°) of geranium at initiation (0 d) of Expt. 1 (DLI = 9 mol·m⁻²·d⁻¹) were 32.9 and 10.1 CIELAB units and 117.9°, respectively, indicating very dark grayish green foliage. Meanwhile, at initiation (0 d) of Expt. 2 (DLI = 11 mol·m⁻²·d⁻¹), average L* and C* values and h° were 33.6 and 10.2 CIELAB units and 106.3°, respectively, also indicating very dark grayish yellow foliage. For fountain grass at initiation (0 d) of Expt. 1, average L* and C* values and h° were 35.5 and 12.7 CIELAB units and 120.4°, indicating pale green foliage. Similarly, under an average DLI of 7.0 mol·m⁻²·d⁻¹, Beckwith et al. (2004) reported fountain grass foliage color of greenhouse-grown plants had light-purple foliage from midleaf to tip, were mostly purple at the top of the canopy, and appeared mostly green in color at the bottom and middle of the canopy. At initiation (0 d) of Expt. 2, average L* and C* values and h° of fountain grass were 30.5 and 6.4 CIELAB units and 81.7°, respectively, indicating slightly green foliage.

In the current study, DLI during Expt. 1 (DLI = 9 mol·m⁻²·d⁻¹) and Expt. 2 (DLI ≥ 11 mol·m⁻²·d⁻¹) influenced foliage color of geranium and fountain grass. In general, EOP SL and days of exposure significantly influenced L* and C* values and h° of geranium (Table 3) and fountain grass (Table 4) when plants were finished under a mean DLI ≤ 9
mol·m⁻²·d⁻¹ and displayed little to no significance under a DLI ≥ 11 mol·m⁻²·d⁻¹. This provides initial evidence that EOP SL is most effective when plants are finished under a low greenhouse DLI of <10 mol·m⁻²·d⁻¹. Furthermore, the parameters measured here to quantify and track foliage color support previous investigations regarding the influence of DLI on coloration and quality of floriculture crops (Garland et al., 2010; Kim et al., 2012). For instance, Garland et al. (2010) reported col cus [Solenostemon scutellarioides (L.) Codd ‘Kong Red’ and ‘Wizard Coral Sunrise’] grown at DLI< 5.8 mol·m⁻²·d⁻¹ for 8 weeks exhibited more green coloration and less burgundy and coral variegations, and plants were considered to be of low quality. Under SSL, Beckwith et al. (2004) found that a DLI of 0.6 to 6.5 mol·m⁻²·d⁻¹ (3 to 160 μmol·m⁻²·s⁻¹ for a 24-h photoperiod) provided by white fluorescent lamps, promoted anthocyanin pigment development and accumulation in the first 48 h, uniform pigmentation of the leaf surface at 3 d, and dark purple leaf color after 7 d. From this study, they concluded that fluorescent SL in the greenhouse may be useful for improving the color and aesthetic value of fountain grass. Therefore, although previous studies have documented the effect of DLI on foliage color of ornamental crops, they have not investigated the influence of light quality or the duration of SL for plants to develop leaf variegation and coloration.

Effects of seasonal DLI on L*. For geranium, as exposure to EOP SL increased from 3 to 14 d under a mean DLI ≤ 9 mol·m⁻²·d⁻¹, L* decreased, indicating darker leaves, under all EOP treatments (Fig. 2), whereas L* values of plants finished under a mean DLI of ≥11 mol·m⁻²·d⁻¹ exhibited fewer significant changes. For example, geranium exposed to as little as 3 d of 100 μmol·m⁻²·s⁻¹ of 50:50 or 100 red:blue light under a mean DLI ≤ 9 mol·m⁻²·d⁻¹ resulted in darker leaves (Table 3). After 14 d of EOP SL providing 100:0, 50:50, or 100 red:blue light delivering 100 μmol·m⁻²·s⁻¹ under a mean DLI ≤ 9 mol·m⁻²·d⁻¹, L* values decreased from 31.0 to 26.8, 29.6 to 27.2, and 30.4 to 26.8 CIELAB units, respectively (Table 3). Furthermore, the lowest L* values (darkest leaves) were measured at 14 d of EOP SL delivering 100 μmol·m⁻²·s⁻¹ provided by 100:0 (26.8 CIELAB units) or 100:50 (26.8 CIELAB units) red:blue light compared with those determined for the control (28.2 CIELAB units) and HPS lamp (28.4 CIELAB units). Maximum foliage darkness was achieved 7 d faster under 100 μmol·m⁻²·s⁻¹ of 100:0 or 87:13 red:blue light than under 50:50 or 100:100 red:blue LEDs providing a similar PPF (Fig. 2). Conversely, Owen and Lopez (2015) reported 100 μmol·m⁻²·s⁻¹ of 50:50 red:blue EOP SL darkened (lower L*) leaves of lettuce ‘Ruby Sky’ 7 d earlier than 100:0 and 100 red:blue EOP SL providing a similar PPF. In the current study, as little as 7 d of 50 μmol·m⁻²·s⁻¹ of 100 red:blue light resulted in comparable foliage darkness compared with plants exposed to 100 μmol·m⁻²·s⁻¹ of 100:0, 87:13, 50:50, or 100 red:blue EOP SL (Table 3). However, 14 d of EOP SL providing 100 red:blue light delivering 100 μmol·m⁻²·s⁻¹ under a mean DLI ≥ 11 mol·m⁻²·d⁻¹ decreased L* values of geranium from 30.9 to 28.0 CIELAB units compared with the control (31.9 to 31.4 CIELAB units).

For fountain grass, as exposure to EOP SL increased from 3 to 21 d, L* values decreased (leaves darkened) under all EOP treatments (Fig. 3). For example, during Expt. 1, from 3 to 21 d of no EOP SL (control) or EOP SL providing 50:50 or 100 red:blue light delivering 100 μmol·m⁻²·s⁻¹, L* values decreased from 35.5 to 31.4, 34.3 to 27.7, and 30.0 to 28.1 CIELAB units, respectively. However, 100 μmol·m⁻²·s⁻¹ of EOP SL providing 100 red:blue light resulted in significantly decreased L* values (darker foliage) 7 d earlier compared with those under 50:50 red:blue light. Therefore, >50% blue light hastened decreases in L* values. Conversely, Owen and Lopez (2015) reported a mean DLI of 6.8 mol·m⁻²·d⁻¹ and 100 μmol·m⁻²·s⁻¹ of EOP SL providing 50:50 red:blue light to significantly decrease L* values of lettuce ‘Cherokee’, ‘Magenta’, and ‘Ruby Sky’ plants within 3 d compared with those under 100:0 or 100 red:blue light.

Under a mean DLI ≥ 11 mol·m⁻²·d⁻¹, exposure to EOP SL from 3 to 14 d resulted in decreasing L* values (darkened leaves) for fountain grass plants under all LED EOP SL treatments. For example, from 3 to 14 d, L* values of plants under 100 μmol·m⁻²·s⁻¹ of EOP SL delivered from 100:0, 87:13, 50:50, or 100 red:blue light decreased from 29.4 to 28.0, 29.6 to 28.2, 28.8 to 27.7, and 28.9 to 27.0 CIELAB units, respectively. However, L* of fountain grass was found to be similar at 14 d when plants were exposed to 100:0, 87:13, 50:50, or 100 red:blue light decreased from 29.4 to 28.0, 29.6 to 28.2, 28.8 to 27.7, and 28.9 to 27.0 CIELAB units, respectively. However, L* of fountain grass was found to be similar at 14 d when plants were exposed to 100:0, 87:13, 50:50, or 100 red:blue light decreased from 29.4 to 28.0, 29.6 to 28.2, 28.8 to 27.7, and 28.9 to 27.0 CIELAB units, respectively. However, L* of fountain grass was found to be similar at 14 d when plants were exposed to 100:0, 87:13, 50:50, or 100 red:blue light decreased from 29.4 to 28.0, 29.6 to 28.2, 28.8 to 27.7, and 28.9 to 27.0 CIELAB units, respectively. However, L* of fountain grass was found to be similar at 14 d when plants were exposed to 100:0, 87:13, 50:50, or 100 red:blue light decreased from 29.4 to 28.0, 29.6 to 28.2, 28.8 to 27.7, and 28.9 to 27.0 CIELAB units, respectively. However, L* of fountain grass was found to be similar at 14 d when plants were exposed to 100:0, 87:13, 50:50, or 100 red:blue light decreased from 29.4 to 28.0, 29.6 to 28.2, 28.8 to 27.7, and 28.9 to 27.0 CIELAB units, respectively. However, L* of fountain grass was found to be similar at 14 d when plants were exposed to 100:0, 87:13, 50:50, or 100 red:blue light decreased from 29.4 to 28.0, 29.6 to 28.2, 28.8 to 27.7, and 28.9 to 27.0 CIELAB units, respectively. However, L* of fountain grass was found to be similar at 14 d when plants were exposed to 100:0, 87:13, 50:50, or 100 red:blue light decreased from 29.4 to 28.0, 29.6 to 28.2, 28.8 to 27.7, and 28.9 to 27.0 CIELAB units, respectively. However, L* of fountain grass was found to be similar at 14 d when plants were exposed to 100:0, 87:13, 50:50, or 100 red:blue light decreased from 29.4 to 28.0, 29.6 to 28.2, 28.8 to 27.7, and 28.9 to 27.0 CIELAB units, respectively.
Table 3. Average leaf lightness (L*), chroma (C*), and hue angle (h°) values of geranium (Pelargonium hortorum ‘Black Velvet’) plants finished under a seasonal daily light integral (DLI) of 9 mol·m⁻²·d⁻¹ (Expt. 1; 1 Apr. 2014) or DLI of 11 mol·m⁻²·d⁻¹ (Expt. 2; 24 Apr. 2014) achieved by using ambient solar light with 16 h of day-extension lighting from low-intensity light-emitting diode (LED) lamps [7:11:33:49:blue:green:red:far-red light ratio (%); control] delivering 4.5 µmol·m⁻²·s⁻¹, or 16 h of supplemental light (SL) from high-pressure sodium (HPS) lamps delivering 70 µmol·m⁻²·s⁻¹, or LED arrays delivering 100 µmol·m⁻²·s⁻¹ of 100:0 red:blue, 100 µmol·m⁻²·s⁻¹ of 87:13 red:blue, 100 µmol·m⁻²·s⁻¹ of 50:50 red:blue, or 25, 50, or 100 µmol·m⁻²·s⁻¹ of 100 red:blue end-of-production (EOP) SL from 3 to 14 d after initiation of EOP lighting treatments.

<table>
<thead>
<tr>
<th>Light source</th>
<th>Control</th>
<th>100:0 red:blue</th>
<th>87:13 red:blue</th>
<th>50:50 red:blue</th>
<th>0:100 red:blue</th>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Days*</td>
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</tr>
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<td>3</td>
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<td>28.4 Bd</td>
<td>29.4 Bb</td>
<td>28.7 Bbc</td>
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<td>28.1 Cab</td>
<td>27.2 Cbc</td>
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</table>

Days of exposure to the control or EOP SL.

Leaf lightness (L*) indicate darkness and lightness (black: L* = 0; white: L* = 100).

Within-column means followed by different upper case letters are significantly different by Fisher’s least significant differences (LSD) at P ≤ 0.05.

Within-row means followed by different lower case letters are significantly different by Fisher’s LSD at P ≤ 0.05.

Chroma (C*) calculated by Eq. [1].

Hue angle (h°) calculated by Eq. [2].

EOP SL resulted in C* values of 4.0, 4.3, or 4.9 CIELAB units, respectively (Table 2). Conversely, under LED SSL, Gangadhar et al. (2012) reported C* of pepper ‘Cheonyang’ fruit to be similar when plants were grown under 50:50 and 0:100 red:blue light compared with 100:0 red:blue SSL delivering 70 µmol·m⁻²·s⁻¹ to achieve a DLI of 4 mol·m⁻²·d⁻¹.

Chroma of geranium finished under a mean DLI of 11 mol·m⁻²·d⁻¹ was not influenced by EOP SL providing 100:0 and 87:13 red:blue delivering 100 µmol·m⁻²·s⁻¹, or LED SSL delivering 70 µmol·m⁻²·s⁻¹ to achieve a DLI of 4 mol·m⁻²·d⁻¹. Under a mean DLI of ≥11 mol·m⁻²·d⁻¹ EOP SL providing increased proportions (%) of red light (100:0 and 87:13) hastened foliage saturation by 5 (100:0 red:blue) and 7 (87:13 red:blue), compared with LED EOP SL providing ≥50% blue light (Table 3). At 14 d of 0:100 red:blue SL increased from 25 to 100 µmol·m⁻²·s⁻¹ under a mean DLI of 9 mol·m⁻²·d⁻¹, C* increased from 3.5 to 5.3 CIELAB units (increased leaf color saturation). However, under a mean DLI of 11 mol·m⁻²·d⁻¹, 14 d of 0:100 red:blue EOP SL providing 100 µmol·m⁻²·s⁻¹ resulted in the greatest saturation (4.5 CIELAB units) compared with all other EOP treatments. Therefore, increased light intensity and light quality played a significant role in darkening and enhancing geranium foliage under low-light greenhouse conditions, such as those at DLIs ≤ 9 mol·m⁻²·d⁻¹. These results are consistent with those reported by Kim et al. (2012) which found increasing DLIs of ≥0.2, 0.4, 0.8, 3.9, and 7.8 mol·m⁻²·d⁻¹ (PPF of ≥2.7, 6.8, 13.5, 67.5, and 135 µmol·m⁻²·s⁻¹) provided by triband phosphor fluorescent lamps decreased C* of English ivy ‘Golden Ingot’.

Fountain grass plants finished under 100 µmol·m⁻²·s⁻¹ of EOP SL delivered from 100.0, 87:13, 50:50, and 0:100 red:blue light under a mean DLI of 9 mol·m⁻²·d⁻¹ exhibited more intense foliage color, thus resulting significantly lower C* values (Table 4). Maximum saturation of fountain grass foliage occurred after 3 d when plants were exposed to 0:100 red:blue EOP SL delivering 100 µmol·m⁻²·s⁻¹. Over time, EOP SL providing 100 µmol·m⁻²·s⁻¹ resulted in less saturated foliage color, whereas light provided by the control increased foliage color saturation. For example, 21 d of EOP SL resulted in C* values of 2.7 to 5.8 CIELAB units for fountain grass plants finished under 100 µmol·m⁻²·s⁻¹. These results are consistent with those reported by Kim et al. (2012) which found increasing DLIs of ≥0.2, 0.4, 0.8, 3.9, and 7.8 mol·m⁻²·d⁻¹ (PPF of ≥2.7, 6.8, 13.5, 67.5, and 135 µmol·m⁻²·s⁻¹) provided by triband phosphor fluorescent lamps decreased C* of English ivy ‘Golden Ingot’.
Table 4. Average leaf lightness (L*), chroma (C*), and hue angle (h°) values of purple fountain grass (Pennisetum advena) plants finished under a seasonal daily light integral (DLI) of 9 mol·m⁻²·d⁻¹ (Expt. 1; 1 Mar. 2014) or DLI of 11 mol·m⁻²·d⁻¹ (Expt. 2; 24 Apr. 2014) achieved by using ambient solar light provided with 16 h of day-extension lighting from low-intensity light-emitting diode (LED) lamps [7:11:33:49 blue:green:red:far-red light ratio (%); control] delivering 4.5 μmol·m⁻²·s⁻¹, or 16 h of supplemental light (SL) from high-pressure sodium (HPS) lamps delivering 70 μmol·m⁻²·s⁻¹, or LED arrays delivering 100 μmol·m⁻²·s⁻¹ of 87:13 red:blue, 100 μmol·m⁻²·s⁻¹ of 50:50 red:blue, or 25, 50, or 100 μmol·m⁻²·s⁻¹ of 100:0 red:blue end-of-production (EOP) SL from 3 to 14 d after initiation of EOP lighting treatments.

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<td>PPF</td>
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<td>Days*</td>
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<td>43.6 Eg</td>
<td>97.5 Dc</td>
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</table>

PPF = photosynthetic photon flux.

*Days of exposure to the control or EOP SL.
*Leaf lightness (L*) indicate darkness and lightness (black: L* = 0; white: L* = 100).
*Within-column means followed by different lower case letters are significantly different by Fisher’s least significant differences (LSD) at P ≤ 0.05.
*Within-row means followed by different upper case letters are significantly different by Fisher’s LSD at P ≤ 0.05.
*Chroma (C*) calculated by Eq. [1].
*Hue angle (h°) calculated by Eq. [2].
*Means with no lettering were found to have no significance.

Effects of seasonal DLI on h°. Hue angle, calculated from a* and b* values, of geranium were significantly influenced by EOP SL and days of exposure. Under seasonal DLIs ≤ 9 and ≥ 11 mol·m⁻²·d⁻¹, the greatest reduction of geranium green foliage color was observed when plants were finished under LED EOP SL providing 100 μmol·m⁻²·s⁻¹ (Table 3). For example, from 3 to 14 d of EOP SL delivering 100 μmol·m⁻²·s⁻¹ provided by 100:0, 87:13, 50:50, and 0:100 red:blue light under a mean DLI ≤ 9 mol·m⁻²·d⁻¹ decreased h° from 85.8° to 15.2°, 92.6° to 11.8°, 73.9° to 11.8°, and 71.3° to 8.7°, respectively; as a result, foliage exhibited violet-red to red hues with increased exposure duration. Consistent with these findings, Owen and Lopez (2015) reported a similar trend for lettuce ‘Magenta’ leaves as h° decreased from 20.1° to 5.9° after 14 d of exposure to 100 μmol·m⁻²·s⁻¹ of 0:100 red:blue EOP SL. However, in the current study, with a mean DLI ≥ 11 mol·m⁻²·d⁻¹, h° was not only influenced by the light quality provided by the EOP SL sources. For instance, 7 d of EOP SL delivering 100 μmol·m⁻²·s⁻¹ provided by 100:0, 87:13, 50:50, and 0:100 red:blue light resulted in h° of 81.4°, 66.2°, 77.7°, and 50.9°, respectively; thus, foliage exhibited yellow-green to orange-red hues. Therefore, increasing DLIs ≥ 11 mol·m⁻²·d⁻¹ may potentially mask the effects of EOP SL when used in the greenhouse to enhance foliage color.

For fountain grass, as exposure to EOP SL increased from 3 to 14 d under a mean DLI ≤ 9 mol·m⁻²·d⁻¹, h° generally decreased (decrease greenness) for all treatments. The greatest reduction of green foliage color was observed when fountain grass was finished under LED EOP SL providing 100 μmol·m⁻²·s⁻¹, compared with light provided by the control, HPS lamps, or 0:100 red:blue providing 25 or 50 μmol·m⁻²·s⁻¹ of EOP SL. For example, 3 to 14 d of EOP SL delivering 100 μmol·m⁻²·s⁻¹ provided by 100:0, 87:13, 50:50, and 0:100 red:blue increased h° from 104.5° to 57.1°, 95.2° to 61.2°, 107.2° to 44.7°, and 77.0° to 3.7°, respectively; thus, fountain grass foliage exhibited violet-red to yellow-orange hues after 14 d of exposure. Increasing
Anthocyanins are responsible for the red or purple pigmentation in flowers and leaves. Although anthocyanin content was not determined in the current study, it is well documented that anthocyanin biosynthesis and accumulation is light regulated and dependent on light intensity and quality (Kataoka et al., 2003; Merzlyak and Chivkunova, 2000; Samuoliene et al., 2012). For instance, Beckwith et al. (2004) determined anthocyanin concentration in purple fountain grass, in percent fresh weight, increased as DLI increased from 2.3 to 7.0 mol·m⁻²·d⁻¹ when plants were grown in the greenhouse under ambient solar daylight with SL provided from HPS lamps. In addition, Paradiso et al. (2011) reported the concentration of anthocyanins in leaf tissue of potted rose (Rosa sp. ‘Akito’) to be higher in reddish leaves (52 ± 15 μmol·m⁻²) than in green leaves (23 ± 10 μmol·m⁻²) when grown in a greenhouse receiving SL from HPS lamps providing a DLI of 5.8 mol·m⁻²·d⁻¹ (PPF of 100 μmol·m⁻²·s⁻¹) under a 16-h photoperiod. Furthermore, Kim et al. (2012) indicated a correlation between anthocyanin content and CIE L*a*b* values (coloration) in polka dot plant. They reported increasing DLIs from 0.2 to 7.8 mol·m⁻²·d⁻¹, provided by triband phosphor fluorescent lamps, increased anthocyanin content, and thus, resulted in decreased L* (darker leaves) and increased a* (increased redness) values in both previously expanded leaves and leaves of young, yellow-orange, and violet-red, respectively, after 14 d of exposure (Fig. 3). Likewise, Owen and Lopez (2015) reported 0:100 red:blue EOP SL delivering 25, 50, or 100 μmol·m⁻²·s⁻¹ for 14 d reduced h° of lettuce ‘Ruby Sky’ leaves by 48.7°, 56.9°, and 112.8°, respectively; thus, resulting in hues of green, green, and red, respectively. Furthermore, Kim et al. (2012) reported increasing DLI = 0.2, 0.4, 0.8, 3.9, and 7.8 mol·m⁻²·d⁻¹ (PPF of 2.7, 6.8, 13.5, 67.5, and 135 μmol·m⁻²·s⁻¹) provided by triband phosphor fluorescent lamps reduced leaf h° of English ivy ‘Golden Ingot’ and polka dot plant, and thus, resulted in increased red color and variegation. However, in the present study, when fountain grass plants were finished under a mean DLI ≥ 11 mol·m⁻²·d⁻¹, h° only differed among EOP SL treatments (Table 4). For instance, 14 d of EOP SL resulted in reduced h° of 11.3° to 41.0° under 100 μmol·m⁻²·s⁻¹ delivered from 100:0, 87:13, 50:50, and 0:100 red:blue light, compared with no EOP SL [control (65.3°)]. In general, fountain grass foliage exhibited red to yellow-orange hues under LED EOP SL.

Fig. 2. Leaf color of geranium (Pelargonium ×hortorum ‘Black Velvet’) finished under 3 to 14 d of day-extension lighting (control) or end-of-production supplemental lighting from high-pressure sodium (HPS) lamps or light-emitting diodes providing red:blue light ratios (%) at either low or high intensities.

Fig. 3. Leaf color of purple fountain grass [Pennisetum ×advena (formerly known as P. setaceum ‘Rubrum’)] finished under 3 to 21 d of day-extension lighting (control) or end-of-production supplemental lighting from high-pressure sodium (HPS) lamps or light-emitting diodes providing red:blue light ratios (%) at either low or high intensities.

Faust, J.E., V. Holcombe, N.C. Rajapakse, and D.R. Berghage. 2000. Consumer Quality, and market value. Also, producers that potentially use this lighting technology for the enhancement of red leaf lettuce in the winter. Our data indicate that bedding plant growers can provide EOP SL with commercially available high-intensity LEDs to increase anthocyanin synthesis and pigmentation of geranium ‘Black Velvet’ and purple fountain grass plants. Although we addressed two challenging bedding plants, popular for their foliage color, similar results can be expected for other floriculture crops with red or purple pigment–variegated leaves but further investigations of EOP SL is needed.

**Conclusion**

EOP SL is a cost-effective alternative for finishing high-quality geranium ‘Black Velvet’ and purple fountain grass plants. The established concept of EOP SL to enhance red leaf lettuce color can be applied to geranium ‘Black Velvet’ and purple fountain grass to enhance leaf color in 7 to 14 d, respectively, thus increasing aesthetic appeal, quality, and market value. Also, producers that only grow bedding plants in the spring could potentially use this lighting technology for the enhancement of red leaf lettuce in the winter.

**Literature Cited**


Faust, J.E., V. Holcombe, N.C. Rajapakse, and D.R. Berghage. 2000. Consumer Quality, and market value. Also, producers that potentially use this lighting technology for the enhancement of red leaf lettuce in the winter. Our data indicate that bedding plant growers can provide EOP SL with commercially available high-intensity LEDs to increase anthocyanin synthesis and pigmentation of geranium ‘Black Velvet’ and purple fountain grass plants. Although we addressed two challenging bedding plants, popular for their foliage color, similar results can be expected for other floriculture crops with red or purple pigment–variegated leaves but further investigations of EOP SL is needed.

**Conclusion**

EOP SL is a cost-effective alternative for finishing high-quality geranium ‘Black Velvet’ and purple fountain grass plants. The established concept of EOP SL to enhance red leaf lettuce color can be applied to geranium ‘Black Velvet’ and purple fountain grass to enhance leaf color in 7 to 14 d, respectively, thus increasing aesthetic appeal, quality, and market value. Also, producers that only grow bedding plants in the spring could potentially use this lighting technology for the enhancement of red leaf lettuce in the winter. Our data indicate that bedding plant growers can provide EOP SL with commercially available high-intensity LEDs to increase anthocyanin synthesis and pigmentation of geranium ‘Black Velvet’ and purple fountain grass plants. Although we addressed two challenging bedding plants, popular for their foliage color, similar results can be expected for other floriculture crops with red or purple pigment–variegated leaves but further investigations of EOP SL is needed.