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End-of-production Supplemental Lighting with Red and Blue Light-emitting Diodes (LEDs) Influences Red Pigmentation of Four Lettuce Varieties

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Abstract**. Under low-light greenhouse conditions, such as those found in northern latitudes, foliage of red leaf lettuce (*****Lactuca sativa*** **L.) varieties is often green and not visually appealing to consumers. Our objective was to quantify the effect of end-of-production (EOP; prior to harvest) supplemental lighting (SL) of different sources and intensities on foliage color of four red leaf lettuce varieties, 'Cherokee', 'Magenta', 'Ruby Sky', and 'Vulcan'. Plants were finished under 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 (control)] delivering 4.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$, or 16-hours of EOP SL from high-pressure sodium (HPS) lamps delivering 70 $\mu mol \cdot m^{-2} \cdot s^{-1}$, or LED arrays [100:0, 0:100, or 50:50 (%) red:blue] delivering 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$, or 0:100 blue LEDs delivering 25 or 50 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Relative chlorophyll content (RCC) and foliage L* (lightness), and chromametric a* (change from green to red) and b* (change from yellow to blue) values were significantly influenced by EOP SL and days of exposure. Generally, RCC of all varieties increased from day 3 to 14 when provided with EOP SL from the HPS lamps and LEDs delivering 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$. End-of-production SL providing 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of 100:0, 0:100, or 50:50 red:blue light for ≥5 days resulted in increasing a* (red) and decreasing L* (darker foliage), b* (blue), and *h*° (hue angle; a measure of tone) for all varieties. Our data suggests that a minimum of 5 days of EOP SL providing 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of 100:0, 0:100, or 50:50 red:blue light enhanced red pigmentation of 'Cherokee', 'Magenta', 'Ruby Sky', and 'Vulcan' leaves when plants are grown under a low greenhouse daily light integrals (DLIs) <10 $mol \cdot m^{-2} \cdot d^{-1}$.**

The production of vegetables and leafy greens in protected and controlled environments can reduce threats associated with field production, and offers the ability to produce crops during the off-season (Zabelitz, 1986). Specifically, greenhouses are controlled environments (Gruda, 2005) where light (quantity, quality, and duration), temperature, relative humidity, CO_2 concentration, and water and nutrient availability are adjusted (Gary, 2003) for optimal plant growth and development. However, ambient photosynthetic DLIs are reduced by up to 50% or more from the greenhouse glazing material, superstructure, and shading (Hanan, 1998). Several studies have indicated that in northern latitudes, the most limiting environmental factor in greenhouse vegetable production is low light (Benoit, 1987; Gaudreau et al., 1994; Grimstad, 1987). For example, Benoit (1987) and Gaudreau et al. (1994) reported that low light levels resulted in the formation of loose heads and low fresh weight of lettuce (*Lactuca sativa* L.), whereas Kleinhenz et al. (2003) reported that shading reduced anthocyanin content of three lettuce cultivars.

Therefore, growers can use high-intensity discharge lamps (HID) such as HPS or metal halide lamps for SL and increase the DLI in the greenhouse. High-intensity LEDs are a promising new SL technology that offer many benefits over the commercially available lamps commonly used in horticulture for SL (Gómez et al., 2013; Morrow, 2008). They are solid-state, semiconducting diodes that can emit light from ≈250 to 1000 nm or greater (Bourget, 2008). The development of LEDs with an output of 1 W or greater has created the potential to use aggregates of LEDs (arrays) as supplemental photosynthetic light sources (Currey and Lopez, 2013). Additionally, LEDs provide narrow-spectrum light in wavebands suitable for plant growth and development, including blue (450 nm), red (660 nm), and far red (730 nm).

Several studies have investigated growth, development, and physiological responses of lettuce grown under LEDs as sole-source lighting (SSL) in indoor-controlled environments (Johkan et al., 2012; Li and Kubota, 2009; Lin et al., 2013; Yorio et al., 2001) or as an SL in greenhouses (Samuolienė et al., 2012). For example, Son and Oh (2013) found combinations of 65:35, 53:47, and 41:59 red (655 nm):blue (456 nm) SSL LEDs to increase chlorophyll content, total phenolic concentration, flavonoid concentration, and antioxidant capacity of lettuce 'Sunmang' (red leaf) and 'Grand Rapid TBR' (green leaf), whereas 100:0 red:blue SSL LEDs to influence lettuce morphology and growth. Thus, the use of LEDs for lettuce growth, development, and spectrum-dependent plant photo-physiological responses is well documented (Samuolienė et al., 2012).

In addition, anthocyanin content of lettuce leaves has been investigated and measured (Li and Kubota, 2009; Samuolienė et al., 2012) and is responsible for the red pigmentation in leaves. Additionally, these pigments have been found to act as potent antioxidants and antibacterial agents (Kong et al., 2003; Richards et al., 2004). Anthocyanin concentration in foliage is dependent on environmental conditions, such as light (quality and intensity) and temperature. Synthesis and accumulation of anthocyanins are induced at high light intensities (Steyn et al., 2002); for example, Richards et al. (2004) reported that total anthocyanin content of lettuce 'Outredgeous' and 'Red Sails' increased as light intensity increased from 150 to 450 $\mu mol \cdot m^{-2} \cdot s^{-1}$. It has also been found that ultraviolet [ultraviolet-B (290 to 320 nm) and ultraviolet-A (320 to 400 nm)], blue (400 to 480 nm), red (600 to 690 nm), and far red (710 to 760 nm) light are responsible for stimulating anthocyanin production (Mancinelli, 1983; Mol et al., 1996). For example, Stutte (2009) reported the addition of blue (440 nm) light significantly increased anthocyanin concentration of leaf tissue and altered the developmental morphology of lettuce plants. Therefore, light influences the amount and distribution of anthocyanins that contribute significantly to leaf color (Gazula et al., 2007).

In horticultural crops, color is a key component that influences and registers with a consumer's initial perception of product quality (Lightbourn et al., 2008; Ryder, 1999) and appeal (Gazula et al., 2007). For example, leaf color (intensity, distribution, or both) is an important quality parameter in lettuce (Gazula et al., 2005). Leaf color is determined primarily by the spectral properties of leaf pigments. The conventional in vitro

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methods for measurement are both destructive and time consuming, involving chlorophyll extraction followed by spectrophotometric measurements (Madeira et al., 2003). However, in vivo chlorophyll measurements can be determined with a portable chlorophyll content meter, resulting in nondestructive and rapid measurements of leaf chlorophyll content based on spectral transmittance properties of leaves (Madeira et al., 2003). While, portable tristimulus colorimeters are used to measure the spectral reflectance properties, such as lightness and chromaticity of fruit and leaf color. Madeira et al. (2003) and León et al. (2007) demonstrated the feasibility of estimating chlorophyll content and color of sweet pepper (*Capsicum annum* L. 'Capistrano') and butterhead lettuce 'Lores', respectively.

To our knowledge, no published information exists on EOP (prior to harvest) SL from LEDs to enhance leaf color of greenhouse-grown red leaf lettuce. Therefore, the objectives of this study were 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 color of four red leaf lettuce varieties. The four red leaf lettuce varieties selected varied in color, leaf morphology, and are available for commercial production.

Materials and Methods

Culture and greenhouse environment. On 30 Sept. (Rep. 1) and 14 Oct. 2013 (Rep. 2), seeds of lettuce 'Cherokee', 'Magenta', 'Ruby Sky', and 'Vulcan' (Johnny's Selected Seeds, Winslow, ME) 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% perlite, and 15% vermiculite (Super Fine Germinating Mix; Sun Gro Horticulture, Agawam, MA). Seedlings were irrigated as necessary with acidified water supplemented with water-soluble fertilizer (Jack's LX 16N–0.94P–12.3K Plug Formula for High Alkalinity Water; J.R. Peters, Inc., Allentown, PA) to provide the following (mg·L^{-1}): 100 N, 10 P, 78 K, 18 Ca, 9.4 Mg, 0.10 B, 0.05 Cu, 0.50 Fe, 0.25 Mn, 0.05 Mo, and 0.25 Zn.

On 21 Oct. (Rep. 1) and 04 Nov. (Rep. 2), 21 d old seedlings were transplanted into 12.7-cm (885 mL) diameter containers (ITML Horticultural Products, Middlefield, OH) filled with a commercial soilless medium comprised of (by volume) 65% peat, 20% perlite, and 15% vermiculite (Fafard 2; Sun Gro Horticulture, Agawam, MA). Plants were irrigated as necessary 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 (Everris, Marysville, OH)] to provide the following (mg·L^{-1}): 200 N, 26 P, 163 K, 50 Ca, 20 Mg, 1.0 Fe, 0.5 Mn and Zn, 0.24 Cu and B, and 0.1 Mo.

Plants 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, 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; Apogee Instruments, Inc., Logan, UT) measured photosynthetic photon flux (*PPF*) every 15 s and the average of each sensor was logged every 15 min by a data logger (WD 2800; Spectrum Technologies, Inc., Aurora, IL). Air temperature was monitored and recorded by a separate aspirated Priva sensor. The greenhouse day and night air temperature set points were 20/18 °C (12 h/12 h). The photoperiod was a constant 16 h (0600 to 2200 HR) consisting of natural daylengths 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. The DLI and average daily temperatures (ADTs) for Reps. 1 and 2 were 8.2 ± 1.2 and 8.3 ± 1.6 mol·m^{-2}·d^{-1} and 19.1 ± 2.1 and 19.0 ± 1.6 °C, respectively.

End-of-production greenhouse environment and supplemental lighting treatments. On 4 Nov. (Rep. 1) and 18 Nov. 2013 (Rep. 2), 35-d-old plants were moved to a glass-glazed greenhouse where the day and night air temperature set points were a constant 18 °C. Five plants of each variety 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 (7:11:33:49 blue:green:red:far red) low intensity LED lamps (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., Beamsville, ON, Canada) or one of five LED arrays (Orbital Technologies Corporation, Madison, WI) providing monochromatic red [100:0 red (660 nm):blue], monochromatic blue [0:100 red:blue (460 nm)], or a combination of red and blue (50:50 red:blue) light (Table 1). Spectral scans of the control and EOP SL treatments were taken at night at the beginning of each replication with a spectroradiometer (PS-100; StellarNet, Inc., Tampa, FL). Spectral quality of light sources is shown in Figure 1. Amplified quantum sensors (SQ-110; Apogee Instruments, Inc., Logan, UT) 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.). The average solar DLI and air temperature after 14 d for Reps. 1 and 2 were 7.1 ± 3.8 and 6.6 ± 2.1 mol·m^{-2}·d^{-1} and 18.5 ± 1.3 and 18.4 ± 0.9 °C, respectively. The supplemental DLI for each treatment was calculated and is reported in Table 1.

Data collection. 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. Leaf color of the same two recently matured leaves was measured using a portable tristimulus colorimeter (CR-200; Konica Minolta Sensing, Inc., NJ) 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 CIE (Commission Internationale de l'Eclairage) 1976 (L*a*b*) color coordinates. The L* value indicates darkness and lightness (black: L* = 0; white: L* = 100). Chromametric a* value is the ratio between greenness and redness (green: a* = –60; red: a* = +60) and chromametric b* value is the ratio between blueness and yellowness (blue: b* = –60; yellow: a* = +60). On a circular scale, hue angle (*h*°) or tone indicates redness (0°), yellowness (90°), greenness (180°), or blueness (270°) and were calculated as

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

Statistical analysis. All plants for each lettuce variety in Reps. 1 and 2 were grown under a common greenhouse environment, therefore average RCC, L*, a*, and b* values were similar before initiating EOP SL treatments (0 d). The experiment used a randomized complete block design. There were five plants per variety (two individual samples per plant) per EOP SL treatment (10 samples per SL treatment) and the experiment was replicated twice over time. Data were not statistically different between replications and were therefore pooled and analyzed using SAS (SAS 9.2; SAS Institute Inc., Cary, NC) mixed model procedure (PROC MIXED) for ANOVA, and means were separated by Fisher's least significant differences (LSD) at $P \leq 0.05$.

Results

Relative chlorophyll content. Relative chlorophyll content of all the varieties in the study was significantly influenced by EOP SL and days of exposure to EOP SL (Table 2). At initiation (0 d), the average RCC of 'Cherokee', 'Magenta', 'Ruby Sky', and 'Vulcan' was 27.3, 28.7, 24.7, and 24.8, respectively. As EOP SL duration increased from 3 to 14 d, RCC of 'Cherokee', 'Magenta', 'Ruby Sky', and 'Vulcan' generally increased with the exception of plants under the control and 0:100 red:blue light at 25 and 50 μmol·m^{-2}·s^{-1} (Table 3). Compared with no EOP SL [control (24.9 and 22.0)], 14 d of EOP SL resulted in RCC of 29.6 to 32.8 and 26.5 to 29.0 for 'Cherokee' and 'Ruby Sky' under 100 μmol·m^{-2}·s^{-1} delivered from 100:0, 0:100, and 50:50 red:blue light.

Leaf lightness. The leaf lightness (L* values) of all varieties were significantly influenced by the interaction between EOP SL and days of exposure (Table 2). At the initiation of EOP SL, the average L* of

Table 1. Lighting manufacturer, spectral color ratio, photon flux, and supplemental daily light integral (DLI) derived from spectral scan taken at night for Rep. 1 (04 Nov. 2013) and Rep. 2 (18 Nov. 2013); structural dimensions, number, spacing, and height from bench level at which lighting treatments were above 'Cherokee', 'Magenta', 'Ruby Sky', and 'Vulcan' lettuce (*Lactuca sativa* L.) plants.

Manufacturer	Ratio (%)	Photon flux (μmol·m^{-2}·s^{-1})		Supplemental DLI (mol·m^{-2}·d^{-1})		Dimensions[z]	Light-emitting diodes (LEDs) per array[y]	No. arrays or lamps[x]	Array or lamp spacing[w] (cm)	Ht[v] (cm)
		Rep. 1	Rep. 2	Rep. 1	Rep. 2					
Philips[u]	7:11:33:49 blue: green:red:far red	4.6 ± 1.2	4.5 ± 1.8	0.3	0.3	—[t]	—	2	79.0	94.6
P.L. Light[s]	—	73.4 ± 18.0	69.0 ± 19.6	4.2	4.0	—	—	1	—	85.5
Orbitec[r]	100:0 red:blue	99.6 ± 60.0	98.6 ± 44.1	5.7	5.7	1.88-cm square, 1.22-m long × 1.30-mm wide	24	7	22.0	69.0
Orbitec	50:50 red:blue	101.2 ± 54.5	97.2 ± 48.6	5.8	5.6	1.20-cm square, 1.22-m long × 1.30-mm wide	28 red, 24 blue	8	15.5	49.0
Orbitec	0:100 red:blue	25.2 ± 3.5	25.6 ± 1.5	1.4	1.5	1.20-cm square, 1.22-m long × 1.30-mm wide	24	8	12.5	35.0
Orbitec	0:100 red:blue	49.0 ± 29.6	48.2 ± 27.0	2.8	2.8	1.20-cm square, 1.22-m long × 1.30-mm wide	24	4	15.5	42.0
Orbitec	0:100 red:blue	100.0 ± 51.8	100.0 ± 42.5	5.8	5.8	1.20-cm square, 1.22-m long × 1.30-mm wide	24	7	22.0	69.0

[z] Dimensions of a single LED array (aggregate of LEDs).

[y] Number of individual LEDs per LED array.

[x] Number of LED arrays per lighting treatment.

[w] Center spacing between LED arrays.

[v] Distance from bench level to LED arrays.

[u] Philips = Koninklijke Philips Electronics N.V., The Netherlands.

[t] No measureable data.

[s] P.L. Light = P.L. Light Systems Inc., Beamsville, ON, Canada.

[r] Orbitec = Orbital Technologies Corporation, Madison, WI.

'Cherokee', 'Magenta', 'Ruby Sky', and 'Vulcan' was 44.9, 46.4, 43.7, and 42.4 CIELAB units, respectively. The L* value of all varieties under 100 μmol·m^{-2}·s^{-1} of EOP SL delivered from 100:0, 0:100, and 50:50 red:blue light for 5 d was significantly lower (resulting in darker foliage) than those under the control (Table 3). As exposure to EOP SL increased from 3 to 14 d, L* values decreased for plants under LED treatments providing 100 μmol·m^{-2}·s^{-1}. Additionally, at 14 d of 0:100 blue light increasing from 25 to 100 μmol·m^{-2}·s^{-1}, L* decreased from 42.5 to 32.9, 49.8 to 32.9, 38.8 to 30.9, and 40.6 to 32.1 for 'Cherokee', 'Magenta' (Fig. 2), 'Ruby Sky', and 'Vulcan', respectively.

*Chromametric a**. The greenness and redness (Chromametric a* value) of all varieties were significantly influenced by EOP SL and days of exposure (Table 2; Fig. 2). At the initiation of EOP SL, the average a* values of 'Cherokee', 'Magenta', 'Ruby Sky', and 'Vulcan' were –13.7, –19.5, –14.9, and –14.4 CIELAB units, respectively. Three days of 100 μmol·m^{-2}·s^{-1} of EOP SL delivered from 100:0, 0:100, and 50:50 red:blue light resulted in a significant increase in a* (resulting in a change in foliage color from green to red) compared with those under the control (Table 4). Over time, EOP SL providing 100 μmol·m^{-2}·s^{-1} resulted in the most rapid increase in a*, whereas light provided by the control, HPS lamps, and low and medium 0:100 red:blue light intensities led to a delayed change in foliage color. For 'Cherokee' and 'Ruby Sky' 14 d under 100 μmol·m^{-2}·s^{-1} of EOP SL delivering 100:0, 0:100, or 50:50 red:blue light resulted in a* values of 3.4 to 4.9 and 3.4 to 4.7 CIELAB, respectively. As the intensity of 0:100 red:blue light increased from 25 to 100 μmol·m^{-2}·s^{-1}, a* values increased over time.

*Chromametric b**. The blueness and yellowness (Chromametric b* value) of all varieties were significantly influenced by EOP SL and days of exposure (Table 2). At the initiation of EOP SL, the average b* of 'Cherokee', 'Magenta', 'Ruby Sky', and 'Vulcan' were 25.2, 27.6, 23.8, and 23.8 CIELAB units, respectively. Three days of 100 μmol·m^{-2}·s^{-1} of EOP SL delivered from 100:0, 0:100, and 50:50 red:blue light resulted in a significant decrease in b* (resulting in a change in foliage color from yellow to blue) compared with those under the control (Table 4). Over time, EOP SL providing 100 μmol·m^{-2}·s^{-1} resulted in a rapid decline in b*, whereas light provided by the control, HPS lamps, and 0:100 red:blue providing 25 and 50 μmol·m^{-2}·s^{-1} of EOP SL led to a delayed change in foliage color. For instance, 14 d of EOP SL resulted in b* values of 4.3 to 7.7 and 5.6 to 6.5 CIELAB units for 'Ruby Sky' and 'Vulcan' under 100 μmol·m^{-2}·s^{-1} delivered from 100:0, 0:100, and 50:50 red:blue light. Additionally, as the intensity of 0:100 red:blue light increased from 25 to 100 μmol·m^{-2}·s^{-1}, b* values decreased over time.

Hue angle. End-of-production SL and days of exposure significantly influenced the hue angle (*h*°) of all varieties, with the exception of

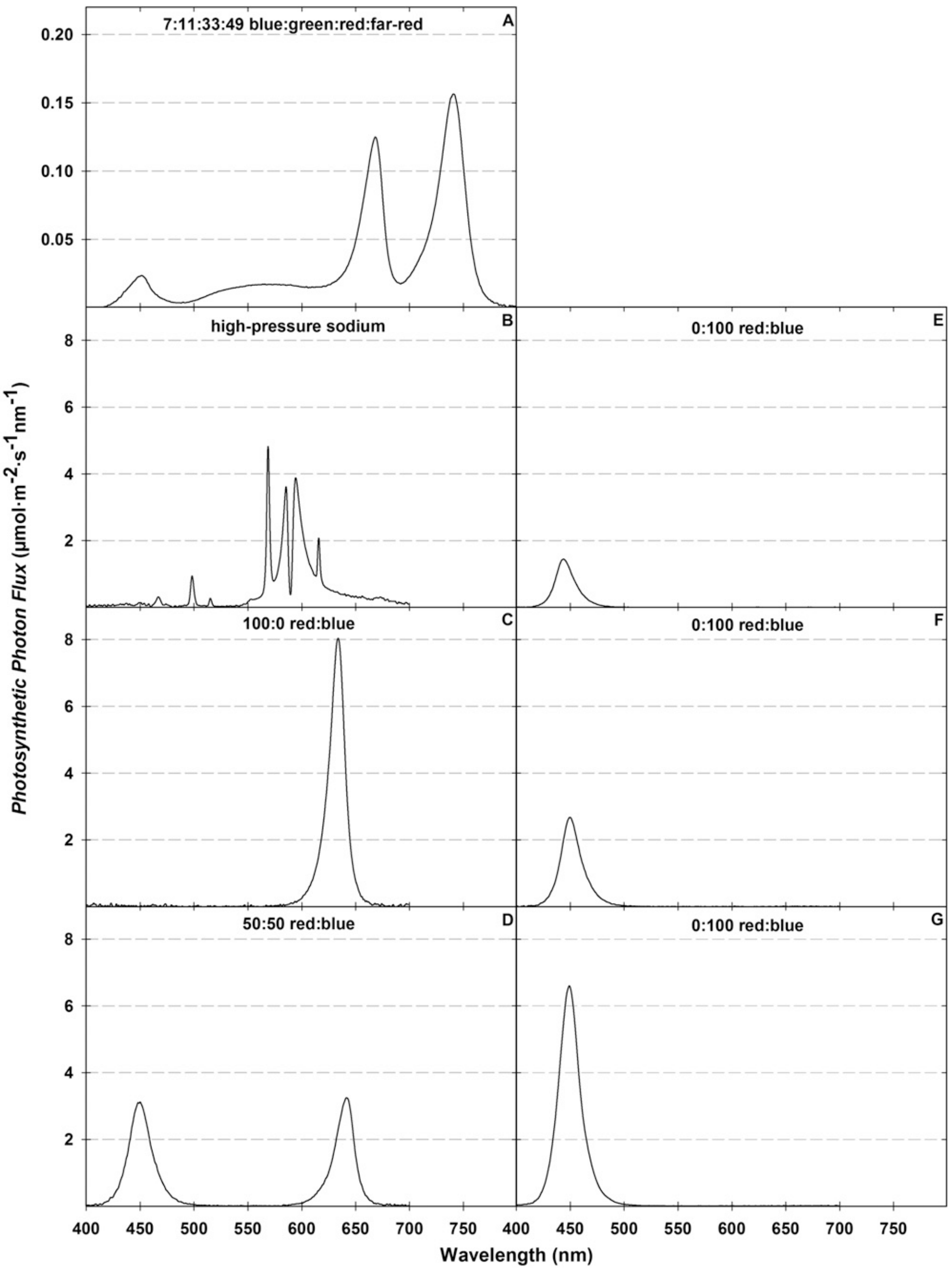

Fig. 1. **(A–G)** Spectral quality of 4.5 µmol·m^{-2}·s^{-1} delivered from day-extension low intensity light-emitting diode (LED) lamps [7:11:33:49 blue:green:red:far red; (control)], or 16 h of **(A)**, 70 µmol·m^{-2}·s^{-1} delivered from high-pressure sodium lamps **(B)**, or LED arrays delivering 100 µmol·m^{-2}·s^{-1} of (%) 100:0 red:blue **(C)**, 100 µmol·m^{-2}·s^{-1} of 50:50 red:blue **(D)**, or 25 **(E)**, 50 **(F)**, or 100 **(G)** µmol·m^{-2}·s^{-1} 0:100 red:blue end-of-production supplemental light.

Table 2. Analyses of variance for the effect of end-of-production supplemental light source (S) and days (D) of exposure on relative chlorophyll content (RCC), leaf lightness (L*), chromametric a* (greenness and redness) and b* (blueness and yellowness) values, and hue angle (*h*°) of ‘Cherokee’, ‘Magenta’, ‘Ruby Sky’, and ‘Vulcan’ lettuce (*Lactuca sativa* L.) plants.

	Cherokee			Magenta			Ruby Sky			Vulcan		
Data	S	D	S × D	S	D	S × D	S	D	S × D	S	D	S × D
RCC	***	***	***	***	***	***	***	***	**	***	***	NS
L*	***	***	**	***	*	***	***	***	*	***	***	**
a*	***	***	**	***	***	***	***	***	NS	***	***	NS
b*	***	***	***	***	***	***	***	***	NS	***	***	**
h°	***	***	NS	NS	NS	NS	***	***	*	***	***	NS

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

‘Magenta’ (Table 2). Average *h*° at initiation was 159.9, 164.8, 161.8, and 161.2°, indicating a green hue. Five days of 100 µmol·m^{-2}·s^{-1} of EOP SL delivered from 100:0, 0:100, and 50:50 red:blue light resulted in a significant decrease in *h*° compared with those under the control (Table 5). Over time, EOP SL providing 100 µmol·m^{-2}·s^{-1} resulted in the greatest reduction of green foliage color, compared with light provided by the control, HPS lamps, and 0:100 red:blue providing 25 or 50 µmol·m^{-2}·s^{-1} of EOP SL. Compared with *h*° at initiation, 7 d of 100:0, 0:100, and 50:50 red:blue providing 100 µmol·m^{-2}·s^{-1} of EOP

Table 3. Average relative chlorophyll content (RCC) and leaf lightness (L*) values of ‘Cherokee’, ‘Magenta’, ‘Ruby Sky’, and ‘Vulcan’ lettuce (*Lactuca sativa* L.) plants finished under 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 (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 50:50 red:blue, or 25, 50, or 100 μmol·m^{-2}·s^{-1} of 0:100 red:blue end-of-production (EOP) SL from 3 to 14 d after initiation of EOP lighting treatments.

	Light source						
	Control	HPS	100:0 red:blue	50:50 red:blue	0:100 red:blue	0:100 red:blue	0:100 red:blue
	PPF[z]						
Days[y]	4.5	70.0	100.0	100.0	25.0	50.0	100.0
				RCC[x]			
				‘Cherokee’			
3	25.8 C[w]b[v]	23.6 Aa	26.3 Ab	28.9 Cd	25.7 Cb	27.3 Cc	26.4 Abc
5	23.1 Aa	23.3 Aa	25.9 Ab	25.8 Ab	23.4 Ba	27.6 Cc	27.3 Bc
7	22.4 Aa	26.1 Bc	27.6 Bd	26.6 Bc	23.1 Ba	24.7 Bb	28.2 Cd
14	24.9 Bc	25.4 Bc	31.1 Ce	32.8 Df	20.6 Aa	23.8 Ab	29.6 Dd
				‘Magenta’			
3	28.4 Ccd	25.4 Ba	25.7 Aa	29.1 Bd	28.1 Dc	29.0 Cd	26.9 Ab
5	23.9 Aa	24.8 Ab	25.1 Ab	26.0 Ac	25.1 Cb	24.9 Bb	28.8 Cd
7	23.6 Aab	24.2 ABb	28.1 Bc	29.1 Bd	23.2 Ba	23.3 Aa	27.8 Bc
14	24.8 Bb	26.6 Cc	29.5 Ce	31.4 Cf	22.5 Aa	24.7 Bb	28.6 Cd
				‘Ruby Sky’			
3	24.1 Bc	20.9 Aa	22.7 Ab	26.1 ABd	23.1 Cbc	23.6 Abc	22.6 Ab
5	22.0 Aa	22.2 Ba	25.6 Bc	26.7 Bc	21.8 Ba	24.0 Ab	24.0 Bb
7	23.6 Bbc	24.5 Ccd	25.4 Bde	25.7 Ae	20.9 Aa	23.3 Ab	23.4 ABbc
14	22.0 Aa	25.8 Dc	27.7 Cd	29.0 Ce	22.9 Cab	23.2 Ab	26.5 Cc
				‘Vulcan’			
3	23.5 Ca	24.2 Aa	27.3 Bc	29.1 Bd	24.5 Ba	24.5 Ca	25.7 Bb
5	20.2 Aa	23.8 Abc	25.4 Ad	27.1 Ae	22.9 Ab	23.3 Bbc	24.1 Ac
7	21.2 Ba	25.4 Bd	27.1 Be	27.8 Ae	22.7 Abc	22.5 Ab	23.7 Ac
14	21.4 Ba	23.8 Ab	28.2 Cd	27.8 Ad	23.0 Ab	23.9 BCb	26.3 Bc
				*L**[u]			
				‘Cherokee’			
3	41.4 Bb	44.1 Bd	40.8 Db	35.1 Ca	43.7 Bcd	42.6 Bc	36.0 Ca
5	43.4 Cd	45.4 Ce	38.1 Cc	32.1 Ba	45.5 Ce	43.4 Bd	35.5 Cb
7	41.8 Bd	41.1 Ad	34.6 Bc	30.3 Aa	43.4 Be	41.0 Ad	31.8 Ab
14	40.0 Ac	44.0 Be	31.9 Aab	31.0 Aa	42.5 Ad	40.8 Ac	32.9 Bb
				‘Magenta’			
3	47.3 Ab	47.6 Ab	47.2 Cb	42.6 Da	46.9 Ab	47.1 Ab	42.9 Ca
5	49.0 Bd	49.1 Cd	47.7 Cc	40.5 Ca	48.8 Bd	47.9 Bc	41.8 Bb
7	49.4 Be	48.8 BCe	44.6 Bc	39.2 Ba	49.0 Be	47.5 ABd	41.1 Ab
14	51.0 Cf	48.4 Bd	41.7 Ac	38.0 Aa	49.8 Ce	48.0 Bd	40.7 Ab
				‘Ruby Sky’			
3	43.4 Bd	41.3 Bc	39.4 Db	35.4 Ca	42.2 Bc	39.2 Bb	34.8 Ca
5	43.8 Bf	41.3 Bd	36.5 Cc	31.5 Ba	42.6 Be	42.2 Cde	34.0 Cb
7	40.0 Ad	38.7 Ac	32.6 Bb	29.6 Aa	39.2 Ad	38.7 Bc	32.1 Bb
14	40.2 Ae	38.3 Acd	31.5 Ab	29.7 Aa	38.8 Ad	37.1 Ac	30.9 Ab
				‘Vulcan’			
3	42.4 Cd	42.7 Cd	37.5 Dc	32.0 Ba	42.0 Bd	38.4 Bc	34.3 Bb
5	44.2 Df	40.5 Be	35.7 Cc	30.8 Aa	43.5 Cf	37.2 Ad	32.5 Ab
7	41.1 Be	39.4 Ad	32.8 Bb	30.2 Aa	40.9 Ae	36.4 Ac	32.9 Ab
14	39.6 Ade	39.4 Acd	29.8 Aa	30.6 Aa	40.6 Ae	38.5 Bc	32.1 Ab

[z] *PPF* = photosynthetic photon flux (μmol·m^{-2}·s^{-1}).

[y] Days of exposure to the control or EOP SL.

[x] RCC [total chlorophyll (a + b)] was estimated using a SPAD chlorophyll meter (SPAD-502; Konica Minolta Sensing, Inc., Osaka, Japan).

[w] Within-column means followed by different upper-case letters are significantly different by Fisher’s least significant differences (LSD) at $P \leq 0.05$.

[v] Within-row means followed by different lower-case letters are significantly different by Fisher’s LSD at $P \leq 0.05$.

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

SL resulted in *h*° ranging from 30.7° to 79.9° and 51.5° to 84.8° for ‘Cherokee’ and ‘Vulcan’, respectively. Thus, foliage exhibited red to red-orange hues. Additionally, as the intensity of 0:100 red:blue light increased from 25 to 100 μmol·m^{-2}·s^{-1}, *h*° decreased over time. Exposure to 3 d of 0:100 red:blue light providing 25 to 100 μmol·m^{-2}·s^{-1} resulted in a decline in *h*° of ‘Cherokee’ from 118.8° to 98.1°, thus indicating an increase in red color.

Discussion

Indicators of lettuce quality include nutritional value, texture, size, shape, flavor, and freedom from defects (Gazula et al., 2007; Kleinhenz et al., 2003). However, leaf color is particularly important because it often influences consumer purchasing behavior and perception of quality. For instance, red leaf lettuce is popular in salad mixes due to the unique colors (anthocyanin content), which contributes to the higher value it fetches compared with green lettuce (Gazula et al., 2007; Mulabagal et al., 2010).

Various approaches, involving environmental, cultural, and management practices, have been used to enhance lettuce quality (Mulabagal et al., 2010). For instance, Gazula et al. (2007) demonstrated a nondestructive instrumental assessment of lettuce leaf color and reported a significant correlation between leaf color and increased anthocyanin levels. Additionally, the U.S. food industry uses instruments for measuring and tracking color changes of fruits and vegetables during processing and storage (Madeira et al., 2003; Wrolstad et al., 2005). Therefore, nondestructive colorimetric instruments can be used to determine and track lettuce leaf color as desired by consumers without damaging leaves or plants.

In the current study, EOP SL (light quality and intensity) and days of exposure all significantly influenced a change in leaf color and intensity for all varieties (Table 2). For ‘Magenta’, exposure to as little as 3 d of 100 μmol·m^{-2}·s^{-1} of 0:100 or 50:50 red:blue light

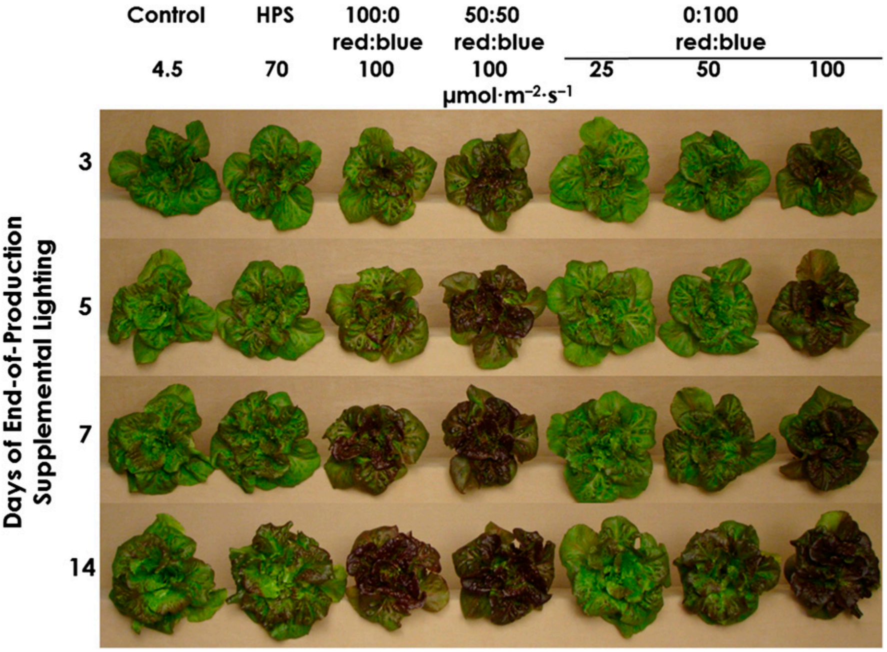

Fig. 2. Leaf color of lettuce (*Lactuca sativa*) ‘Cherokee’ finished under 3 to 14 d of day-extension lighting (control) or end-of-production supplemental lighting from high-pressure sodium lamps or light-emitting diodes providing monochromatic red, blue, red:blue light at either low or high intensities.

resulted in darker leaves (Table 3). Maximum foliage coloration for ‘Ruby Sky’ was achieved 7 d faster under 50:50 red:blue providing 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of EOP SL than plants under 100:0 or 0:100 red:blue LEDs providing a similar *PPF*. Seven days of 50:50 red:blue EOP SL delivering 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ resulted in the maximum chromametric a* values for ‘Cherokee’ compared with 14 d or more for 100:0 and 0:100 red:blue EOP SL delivering a similar *PPF* (Table 3; Fig. 2). Furthermore, 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of monochromatic blue EOP SL hastened red pigment accumulation in ‘Cherokee’ leaves by 7 d compared with monochromatic red EOP SL. In general, ‘Cherokee’ leaves decreased in chromametric b* values over time. The minimum, stable chromametric b* values were recorded in just 7 d for ‘Cherokee’ plants under 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of 0:100 and 50:50 red:blue EOP SL, while they continued to decrease in all other treatments from 7 to14 d. Additionally, leaf redness, blueness, and darkness increased and yellowness decreased as the intensity of monochromatic blue EOP SL increased from 25 to 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Therefore, increased light intensity played a significant role in darkening lettuce foliage. However, light quality also influenced lettuce foliage L*, a*, and b*.These finding indicate that different varieties respond differently to light intensity and quality.

Similar to our findings, Gangadhar et al. (2012) reported maximum pepper (*Capsicum annuum* L. ‘Cheonyang’) fruit redness (a*) to occur when plants were grown under 50:50 red:blue and monochromatic blue sole-source LEDs compared with monochromatic red LEDs. Whereas, Beckwith et al. (2004) investigated color development in purple fountain grass [*Pennisetum setaceum* (Forssk.) Chiov. ‘Rubrum’] leaves overtime. Plants were grown under white fluorescent lamps providing 3 to 160 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (0.6 to 6.5 $mol \cdot m^{-2} \cdot d^{-1}$) for 10 d. Chromametric a* values increased as light quantity increased, thus promoting anthocyanin pigment development in the first 48 h, uniform pigmentation of the leaf surface at 3 d, and dark purple leaf color after 7 d. They concluded SL fluorescent lighting in the greenhouse may be useful for improving the color and aesthetic value of purple fountain grass.

Calculated *h*° from a* and b* values of ‘Ruby Sky’ leaves were significantly influenced by EOP SL and days of exposure. For example, *h*° of ‘Ruby Sky’ leaves under the control and 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of 50:50 red:blue EOP SL decreased from 114.8° to 98.7° and 95.3° to 40.6° from 3 to 14 d, respectively. Higher *h*° observed for the control is related to lower a* and higher b* values, indicating a green hue, compared with lower *h*° and a* and higher b* values indicating a red hue observed in plants finished under 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of 50:50 red:blue EOP SL. Also, increasing intensity of 0:100 red:blue EOP SL decreased *h*° from 3 to 14 d. For instance, *h*° of ‘Ruby Sky’ leaves under 25, 50, or 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of 0:100 red:blue EOP SL decreased from 118.8° to 114.5°, 117.4° to 112.1°, and 98.1° to 55.8° with resulting hues of green, green, and red, respectively. Similarly, Kim et al. (2012) reported that fully expanded and recently expanded English ivy (*Hedera helix* L. ‘Golden Ingot’) and polka dot plant (*Hypoestes phyllostachya* Baker) leaves had decreasing *h*° with increasing *PPF* of ≈2.7, 6.8, 13.5, 67.5, and 135 $\mu mol \cdot m^{-2} \cdot s^{-1}$ provided by triband phosphor fluorescent lamps delivering a 16-h photoperiod in a laboratory. They indicated that a *PPF* of 135 $\mu mol \cdot m^{-2} \cdot s^{-1}$ resulted in increased red color, variegation, and anthocyanin content of polka dot plant leaves.

The intensity and distribution of chlorophylls and anthocyanins are known to contribute significantly to leaf color (Gazula et al., 2007) and environmental factors such as light quantity, quality, and duration, and temperature can strongly influence the accumulation of these pigments. We determined that the RCC of all the lettuce varieties was greatest when plants were finished under 100:0, 0:100 or 50:50 red:blue EOP SL delivering 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ compared with those under ambient light (control) and HPS SL lighting. Similarly, Son and Oh (2013) reported RCC of lettuce ‘Sunmang’ and ‘Grand Rapid TBR’ increased when they were finished under 171 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of sole-source LED lighting providing up to 47% and 26% blue light, respectively.

Anthocyanins, which are responsible for the red pigmentation in leaves, have been suggested to offer an array of health-promoting benefits. Mulabagal et al. (2010) reported higher phenolic and anthocyanin levels present in red leaf lettuce ‘Cherokee’; thus consumption of red lettuce could provide better health-benefits than green leaf lettuce. Although anthocyanin content was not quantified in this study, it is well documented that anthocyanins generally accumulate in expanding leaves and in peripheral tissues, such as the upper epidermis, when exposed to direct light (Steyn et al., 2002). Previous reports indicated that anthocyanin biosynthesis is light regulated and dependent on light intensity and quality (Kataoka et al., 2003; Merzlyak and Chivkunova, 2000; Samuoliené et al., 2012). Therefore, this provides additional support of our observations that exposure to high-intensity LED EOP SL stimulates anthocyanins and our measured change in lettuce leaf color.

To determine if SL blue light could stimulate anthocyanin accumulation in leaves, Li and Kubota (2009) grew lettuce ‘Red Cross’ under sole-source white fluorescent lamps providing a *PPF* of 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ alone or supplemented with LEDs providing a photon flux of 18 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of ultraviolet-A (373 nm), 130 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of blue (476 nm), green (526 nm), or red (658 nm), or 160 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of far red (734 nm) light for 16 h. They confirmed that total anthocyanin concentration was greatest and increased with blue light. Additionally, Stutte (2009) reported anthocyanin concentration of lettuce ‘Outredgeous’ grown under sole-source triphosphor fluorescent lamps or red (640 nm): green (530 nm):blue (440 nm), red:blue, monochromatic red, or red:far red (730 nm) LEDs providing 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (DLI ≈19.4 $mol \cdot m^{-2} \cdot d^{-1}$) was over twice as high in the presence of blue light than red light alone. Conversely, Heo et al. (2012) found anthocyanin accumulation in lettuce ‘Ttuksum’ and ‘Jaju’ was promoted by 50:50 red:blue LEDs and inhibited by monochromatic blue LEDs when plants were grown under

Table 4. Average chromametric a* (greenness and redness) and b* (blueness and yellowness) values of 'Cherokee', 'Magenta', 'Ruby Sky', and 'Vulcan' lettuce (*Lactuca sativa* L.) plants finished under 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 (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 50:50 red:blue, or 25, 50, or 100 µmol·m^{-2}·s^{-1} of 0:100 red:blue end-of-production (EOP) SL from 3 to 14 d after initiation of EOP lighting treatments.

	Light Source						
	Control	HPS	100:0 red:blue	50:50 red:blue	0:100 red:blue	0:100 red:blue	0:100 red:blue
	PPF^{z}						
Days^{y}	4.5	70.0	100.0	100.0	25.0	50.0	100.0
*a**^{x}							
'Cherokee'							
3	–9.6 A^{w}c^{v}	–11.9 Aab	–7.8 Ad	–1.0 Ae	–13.1 Aa	–11.1 Ab	–1.8 Ae
5	–8.6 Ac	–11.4 Ab	–1.5 Bd	2.9 Bf	–12.8 Aa	–10.5 Ab	0.5 Be
7	–5.7 Bc	–5.9 Cc	1.6 Cd	5.9 Ce	–9.4 Ba	–7.9 Bb	5.5 De
14	–2.2 Cc	–9.3 Ba	4.5 Dde	4.9 Ce	–8.7 Ba	–6.4 Cb	3.4 Cd
'Magenta'							
3	–19.5 Aa	–19.4 Aa	–18.0 Ab	–12.1 Ac	–19.0 Aa	–17.9 Ab	–11.3 Ac
5	–18.9 ABab	–19.2 Aa	–17.1 Bc	–8.8 Be	–18.6 Aab	–18.2 Ab	–10.1 Bd
7	–18.6 Ba	–18.9 Aa	–14.3 Cc	–6.4 Cd	–18.6 Aa	–16.8 Bb	–5.9 Cd
14	–17.8 Ca	–17.4 Ba	–9.8 Dc	–5.6 Dd	–17.2 Ba	–15.4 Cb	–5.5 Cd
'Ruby Sky'							
3	–12.2 Aa	–11.2 Aa	–8.3 Ab	–2.5 Ac	–12.3 Aa	–9.2 Ab	–0.9 Ad
5	–11.4 Aa	–9.4 Bb	–2.5 Bc	1.2 Bd	–11.7 Aa	–9.6 Ab	1.0 Bd
7	–6.4 Ba	–6.4 Ca	2.1 Cb	4.2 Cc	–7.2 Ba	–6.4 Ba	3.2 Cbc
14	–6.1 Bab	–5.6 Cb	3.4 Dd	3.8 Cd	–7.5 Ba	–3.9 Cc	4.7 Dd
'Vulcan'							
3	–11.8 Ab	–14.0 Aa	–5.5 Ad	2.8 Af	–12.6 Aab	–7.6 Ac	–0.8 Ae
5	–12.2 Aa	–9.3 Bb	–1.1 Bd	3.6 Abe	–12.7 Aa	–4.0 BCc	2.3 Be
7	–7.5 Bb	–8.7 BCb	1.0 Cd	4.7 Be	–10.4 Ba	–3.3 Cc	2.6 Bd
14	–5.7 Cb	–7.6 Ca	3.8 Dc	3.9 ABc	–8.6 Ca	–4.6 Bb	3.9 Cc
*b**^{u}							
'Cherokee'							
3	20.8 Cd	23.5 Cf	19.2 Dc	10.7 Da	23.8 Cg	21.4 De	12.6 Cb
5	21.0 Dd	23.4 Ce	14.0 Cc	6.3 Ca	24.3 Df	20.9 Cd	10.7 Bb
7	18.3 Be	17.5 Ad	9.0 Bc	3.5 Aa	20.6 Bf	17.6 Bd	5.0 Ab
14	14.4 Ad	20.1 Bg	5.6 Ac	4.2 Ba	19.1 Af	15.8 Ae	5.0 Ab
'Magenta'							
3	28.1 Af	27.9 Be	26.7 Cc	20.4 Db	27.0 Ad	26.7 Cc	20.1 Da
5	29.1 Cf	29.2 Dg	27.6 Dd	18.1 Ca	28.2 Ce	27.3 Dc	19.5 Cb
7	29.2 Bg	28.3 Cf	24.3 Bc	15.9 Ba	28.2 Ce	26.3 Bd	16.5 Bb
14	28.8 Dg	27.4 Ae	19.5 Ac	14.3 Aa	27.5 Bf	25.2 Ad	14.9 Ab
'Ruby Sky'							
3	22.6 Cg	20.6 Ce	18.3 Dc	11.6 Db	22.3 Cf	19.1 Cd	11.3 Da
5	22.9 Df	21.3 De	14.6 Cc	8.8 Ca	23.0 Df	20.4 Dd	10.6 Cb
7	19.3 Bf	17.3 Bd	9.6 Bc	6.1 Ba	18.3 Be	17.4 Bd	8.5 Bb
14	17.4 Af	15.3 Ae	7.7 Ac	4.3 Aa	17.6 Af	14.7 Ad	5.4 Ab
'Vulcan'							
3	21.8 Cf	23.0 Dg	16.3 Dc	6.8 Ca	21.6 Ce	17.0 Dd	10.6 Db
5	23.6 Dg	20.7 Ce	13.1 Cc	5.8 Ba	22.3 Df	14.8 Cd	8.5 Bb
7	19.4 Be	19.6 Bf	10.9 Bc	5.9 Ba	20.3 Bg	13.9 Ad	8.8 Cb
14	17.4 Ae	18.0 Af	6.5 Ac	5.6 Aa	18.8 Ag	14.1 Bd	5.9 Ab

[z] *PPF* = photosynthetic photon flux (µmol·m^{-2}·s^{-1}).

[y] Days of exposure to the control or EOP SL.

[x] Chromametric a* value is the ratio between greenness and redness (green: a* = –60; red: a* = +60).

[w] Within-column means followed by different upper-case letters are significantly different by Fisher's least significant differences (LSD) at $P \leq 0.05$.

[v] Within-row means followed by different lower-case letters are significantly different by Fisher's LSD at $P \leq 0.05$.

[u] Chromametric b* value is the ratio between blueness and yellowness (blue: b* = –60; yellow: b* = +60).

sole-source fluorescent lamps (control), or 100:0, 0:100, or 50:50 red (660 nm):blue (450 nm) LEDs delivering 90 ± 10 µmol·m^{-2}·s^{-1} (DLI ≈4.6 to 5.8 mol·m^{-2}·d^{-1}) for 16 h. The previously mentioned studies demonstrate successful culture and enhancement of anthocyanin concentration in multiple lettuce varieties under SSL. Samuolienė et al. (2012) investigated lettuce 'Multired 4' grown in a greenhouse under HPS lamps providing 170 µmol·m^{-2}·s^{-1} with the addition of blue (455 or 470 nm) or green (505 or 530 nm) LEDs delivering 30 µmol·m^{-2}·s^{-1} for 16 h. The authors concluded that SL with blue light (455 and 470 nm) enhanced anthocyanin content. Therefore, sole-source and supplemental monochromatic blue and red:blue light provided by LEDs have been successfully used to promote anthocyanin accumulation and leaf color of lettuce during the entire production cycle.

Conclusion

A range of red leaf lettuce that varied in color, from dark vivid red to candy-apple red, and leaf morphology (sinuate) were selected for this study. Regardless of leaf color or morphology, all varieties grown under low ambient greenhouse light developed darker red foliage and had increased RCC after exposure to EOP SL providing 100 µmol·m^{-2}·s^{-1} from monochromatic red or blue or 50:50 red:blue LEDs. Our results collectively indicate that 5 to 7 d of exposure to LED EOP SL before harvest or shipping enhanced the foliage color and intensity, as well as aesthetic quality of 'Cherokee', 'Magenta', 'Ruby Sky', and 'Vulcan' (Fig. 2).

End-of-production SL demonstrates an alternative and cost-effective, preharvest greenhouse SL practice for lettuce production in northern latitudes. The novel concept of EOP SL can allow growers to manipulate leaf color in 5 to 7 d, thus increasing aesthetic appeal, quality, and market value without negatively affecting growth or morphology. Additionally, EOP SL could provide economic benefits by reducing the number of LEDs that would be needed if the crop was placed under SL for the entire production cycle.

Table 5. Average hue angles (h°) of 'Cherokee', 'Magenta', 'Ruby Sky', and 'Vulcan' lettuce (*Lactuca sativa* L.) plants finished under 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 (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 50:50 red:blue, or 25, 50, or 100 μmol·m^{-2}·s^{-1} of 0:100 red:blue end-of-production (EOP) SL from 3 to 14 d after initiation of EOP lighting treatments.

	Light source						
	Control	HPS	100:0 red:blue	50:50 red:blue	0:100 red:blue	0:100 red:blue	0:100 red:blue
	PPF[z]						
Days[y]	4.5	70.0	100.0	100.0	25.0	50.0	100.0
	h°[x]						
	'Cherokee'						
3	114.8 D[w]d[v]	116.9 De	112.1 Dc	95.3 Da	118.8 Cg	117.4 Df	98.1 Db
5	112.3 Cd	116.0 Ce	96.1 Cc	65.3 Ca	117.8 Bg	116.7 Cf	87.3 Cb
7	107.3 Bd	108.6 Ae	79.9 Bc	30.7 Aa	114.5 Ag	114.2 Bf	42.3 Ab
14	98.7 Ad	114.8 Bg	51.2 Ab	40.6 Ba	114.5 Af	112.1 Ae	55.8 Bc
	'Magenta'						
3	124.8 De	124.8 De	124.0 Dd	120.7 Db	125.1 Cf	123.8 Dc	119.3 Da
5	123.0 Cd	123.3 Be	121.8 Cc	115.9 Ca	123.4 Be	123.7 Cf	117.4 Cb
7	122.5 Bd	123.7 Cf	120.5 Bc	111.9 Bb	123.4 Be	122.6 Bd	109.7 Aa
14	121.7 Ae	122.4 Ag	116.7 Ac	111.4 Ab	122.0 Af	121.4 Ad	110.3 Ba
	'Ruby Sky'						
3	118.4 De	118.5 De	114.4 Dc	102.2 Db	118.9 Df	115.7 Dd	94.6 Da
5	116.5 Cf	113.8 Cd	99.7 Cc	82.2 Ca	117.0 Cg	115.2 Ce	84.6 Cb
7	108.3 Ad	110.3 Be	77.7 Bc	55.5 Ba	111.5 Af	110.2 Be	69.4 Bb
14	109.3 Be	110.1 Af	66.2 Ac	48.5 Aa	113.1 Bg	104.9 Ad	49.0 Ab
	'Vulcan'						
3	118.4 De	121.3 Dg	108.6 Dc	67.6 Da	120.3 Df	114.1 Dd	94.3 Db
5	117.3 Cf	114.2 Ce	94.8 Cc	58.2 Ca	119.7 Cg	105.1 Bd	74.9 Cb
7	111.1 Be	113.9 Bf	84.8 Bc	51.5 Aa	117.1 Bg	103.4 Ad	73.5 Bb
14	108.1 Ad	112.9 Ae	59.7 Ac	55.1 Ba	114.6 Af	108.1 Cd	56.5 Ab

[z] *PPF* = photosynthetic photon flux (μmol·m^{-2}·s^{-1}).

[y] Days of exposure to the control or EOP SL.

[x] Hue angle (h°) calculated by Eq. [1].

[w] Within-column means followed by different upper case letters are significantly different by Fisher's least significant differences (LSD) at $P \leq 0.05$.

[v] Within-row means followed by different lower case letters are significantly different by Fisher's LSD at $P \leq 0.05$.

Furthermore, our data indicates that growers can provide EOP SL with commercially available high-intensity LEDs to increase anthocyanin synthesis and pigmentation of their lettuce crops.

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