Comparison of Bedding Plant Seedlings Grown Under Sole-source Light-emitting Diodes (LEDs) and Greenhouse Supplemental Lighting from LEDs and High-pressure Sodium Lamps

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Abstract. To produce uniform, compact, and high-quality annual bedding plant seedlings in late winter through early spring, growers in northern latitudes must use supplemental lighting (SL) to achieve a photosynthetic daily light integral (DLI) of 10 to 12 mol·m⁻²·d⁻¹. Alternatively, new lighting technologies may be used for sole-source photosynthetic lighting (SSL) to grow seedlings in an indoor high-density multilayer controlled environment. The objective of this study was to compare seedlings grown under low greenhouse ambient light (AL) to those grown under SL or SSL with a similar DLI. On hypocotyl emergence, seedlings of vinca (*Catharanthus roseus*), impatiens (*Impatiens walleriana*), geranium (*Pelargonium × hortorum*), petunia (*Petunia × hybrida*), and French marigold (*Tagetes patula*) were placed in a greenhouse under AL or AL plus SL delivering a photosynthetic photon flux (PPF) of 70 μmol·m⁻²·s⁻¹ for 16 hours, or under multilayer SSL delivering a PPF of 185 μmol·m⁻²·s⁻¹ for 16 hours in a walk-in growth chamber. Supplemental lighting consisted of high-pressure sodium (HPS) lamps or high-intensity light-emitting diode (LED) arrays with a red:blue light ratio (400–700 nm; %) of 87:13, and SSL consisted of LED arrays providing a red:blue light ratio (%) of 87:13 or 70:30. Root and shoot dry mass, stem diameter, relative chlorophyll content, and the quality index (a quantitative measurement of quality) of most species were generally greater under SSL and SL than under AL. In addition, height of geranium, petunia, and marigold was 5% to 26%, 62% to 79%, and 7% to 19% shorter, respectively, for seedlings grown under SSL compared with those under AL and SL. With the exception of impatiens, time to flower was similar or hastened for all species grown under SL or SSL compared with AL. Seedlings grown under SSL were of similar or greater quality compared with those under SL, indicating that LED SSL could be used as an alternative to traditional greenhouse seedling production.

Young plants are commonly produced from vegetative cuttings or seeds during late winter and early spring (Klopmeier et al.,

2003; Styer, 2003). However, during peak young plant production, the average greenhouse photosynthetic DLI can be as low as 1 to 5 mol·m⁻²·d⁻¹ in northern latitudes leading to decreased quality (Lopez and Runkle, 2008; Pramuk and Runkle, 2005). Previous research has determined that a DLI of 10 to 12 mol·m⁻²·d⁻¹ is necessary to produce high-quality young plants (Currey et al., 2012; Hutchinson et al., 2012; Lopez and Runkle, 2008; Oh et al., 2010; Pramuk and Runkle, 2005; Randall and Lopez, 2014). The only way to appreciably increase DLI during young plant production is through the use of overhead SL (Oh et al., 2010; Randall and Lopez, 2014; Sherrard, 2003).

High-intensity discharge lamps, such as HPS and metal halide lamps, have traditionally been used for SL to increase greenhouse DLI. High-pressure sodium lamps have long been the most efficient SL source, converting ≈25% to 30% of their electrical energy into photosynthetically active radiation [PAR

(400 to 700 nm)] with an operational lifespan of 10,000 luminous hours or more (Spaargaren, 2001). However, as much as 72% of the PAR emitted by HPS lamps is in the 565 to 590 nm (yellow) and 590 to 625 nm (orange) wavebands. Moreover, up to 75% of the electrical energy used by HPS lamps is emitted as radiant heat, and the surface of the bulb can reach temperatures as high as 450 °C, thus requiring plants to be separated from the lamps to avoid leaf scorch (Fisher and Both, 2004; Sherrard, 2003; Spaargaren, 2001).

In recent years, some alternatives to HPS lamps have been introduced, including plasma lamps and high intensity LEDs. Light-emitting diodes are solid-state, single junction semiconductors that are capable of producing light wavelengths as short as 250 nm and up to greater than 1000 nm. Thus, they are useful for testing specific wavelength combinations for plant growth and morphology (Folta and Childers, 2008; Randall and Lopez, 2014; Stutte, 2009). They also radiate minimal heat toward the plant canopy, allowing lights to be placed close to crops. Until recently, LEDs were low power (<1 W) and impractical for SL (Bourget, 2008).

Due to their small size, wavelength specificity, high light output, and relatively low heat output, LEDs have been used in environmental chambers for SSL (Heo et al., 2006; Wollaeger and Runkle, 2013, 2014) or in greenhouses as overhead SL (Currey and Lopez, 2013; Randall and Lopez, 2014) for ornamental young plants. For example, Heo et al. (2006) grew seedlings of African marigold (*Tagetes erecta* ‘Orange Boy’), ageratum (*Ageratum houstonianum* ‘Blue Field’), and salvia (*Salvia splendens* ‘Red Vista’) for 28 d at 25 ± 2 °C under a 16-h photoperiod from SSL LEDs delivering a PPF of 90 ± 10 μmol·m⁻²·s⁻¹ (DLI ≈ 5 mol·m⁻²·d⁻¹) at a 1:1 ratio of red:blue, blue:far-red, red:far-red light, or under cool-white fluorescent lamps (CWFL). After 28 d, leaf area of ageratum and salvia grown under the red:blue LEDs increased by 100% to 122% and 42% to 66%, respectively, compared with the other LED treatments and was similar to plants under CWFL. In addition, height of ageratum, marigold, and salvia was reduced by 35% to 69%, 44% to 56%, and 57% to 64%, respectively, under the red:blue LEDs compared with the other LED treatments while remaining similar to the plants under the CWFL (Heo et al., 2006). Another study compared seedlings of impatiens ‘SuperElfin XP Red’, petunia ‘Wave Pink’, tomato (*Solanum lycopersicum* ‘Early Girl’), and African marigold ‘Deep Orange’ grown under SSL with an 18-h photoperiod and PPF of 160 μmol·m⁻²·s⁻¹ (DLI ≈ 9 mol·m⁻²·d⁻¹) delivered from LEDs providing 10% blue and 10% green light with the following combinations (%) of orange (peak = 596 nm), red (peak = 634 nm), and hyper-red (peak = 664 nm): 20:30:30, 0:80:0, 0:60:20, 0:40:40, 0:20:60, or 0:0:80. Height of tomato and marigold was 18% and 13% shorter under

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the 0:40:40 than the 0:80:0 orange:red:hyper-red LEDs, respectively, but was similar to the other light treatments; and shoot dry mass (SDM) of tomato was 25% to 40% greater under the 0:60:20 orange:red:hyper-red than under SSL providing 0:40:40, 0:20:60, or 0:0:80 orange:red:hyper-red light (Wollaeger and Runkle, 2013). Finally, Randall and Lopez (2014) compared seedlings of snapdragon (*Antirrhinum majus* 'Rocket Pink'), vinca 'Titan Punch', celosia (*Celosia argentea* 'Fresh Look Gold'), impatiens 'Dazzler Blue Pearl', geranium 'Bullseye Scarlet', petunia 'Plush Blue', salvia 'Vista Red', French marigold 'Bonanza Flame', and pansy (*Viola xwittrockiana* 'Mammoth Big Red') grown under AL supplemented with a *PPF* of 100 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for 16 h from either HPS or one of three LED arrays composed of (%) 100:0, 85:15, or 70:30 red:blue light. After 28 d, height of all species except snapdragon and geranium was reduced by 9% to 55% under 85:15 red:blue LEDs compared with those under HPS lamps; and stem diameter of geranium, marigold, and snapdragon was 8% to 16% greater under 85:15 red:blue LEDs compared with seedlings grown under HPS lamps.

To our knowledge, no studies have compared annual bedding plant seedlings grown under SSL to those grown under SL in a greenhouse providing the same DLI. The objectives of this study were to 1) quantify the effects of SL from HPS lamps and LED arrays compared with a SSL multilayer production system from LED arrays providing two different light qualities on seedling growth, morphology, and quality and 2) determine whether there were any residual effects of either SL or SSL on subsequent flowering.

Materials and Methods

Plant material, culture, and propagation environment. Seeds of French marigold 'Durango Yellow', geranium 'Bullseye Red', impatiens 'Super Elfin XP Blue Pearl', petunia 'Dreams Midnight', and vinca 'Titan Red Dark' (Ball Horticulture Co., West Chicago, IL) were sown into 288-cell (6-mL individual cell volume) seed trays filled with a commercial soilless medium composed of (by volume) 65% peat, 20% perlite, and 15% vermiculite (Fafard Super Fine Germinating Mix; Sun Gro Horticulture, Agawam, MA) and placed in a glass-glazed greenhouse at Purdue University, West Lafayette, IN (latitude 40°N). Exhaust fan and evaporative-pad cooling, radiant hot water heating, and retractable shade curtains were controlled by an environmental control system (Maximizer Precision 10; Priva Computers Inc., Vineland Station, Ontario, Canada). The DLI and average daily temperatures (ADT) for seasons I, II, and III from sowing to hypocotyl emergence were 12.1 ± 1.7 , 11.4 ± 2.8 , and 12.3 ± 1.8 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, and 22.6 ± 0.8 , 22.3 ± 1.1 , and 22.4 ± 1.1 °C, respectively. On hypocotyl emergence, two trays of each species were moved under either AL, AL plus

SL in a glass-glazed greenhouse, or SSL in a growth chamber.

Greenhouse environment. All species were placed under a 16-h photoperiod with ADTs of 22.6 ± 0.9 , 22.7 ± 0.7 , and 22.7 ± 2.8 °C for seasons I, II, and III, respectively. Infrared temperature sensors with an emissivity of 0.95 (OS136; Omega Engineering, Inc., Stamford, CT) recorded seedling canopy temperatures every 30 s and averages were logged every 15 min by a data logger (Maximizer Precision 10). Quantum sensors (SQ-110; Apogee Instruments Inc., Logan, UT) measured solar *PPF* every 15 s and the average was logged every 15 min by a data logger (WD 2800; Spectrum Technologies, Aurora, IL). Environmental data for the greenhouse environment are reported in Table 1. Seedlings were irrigated with 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) providing (in $\text{mg}\cdot\text{L}^{-1}$): 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.

Growth chamber environment. All species were placed under a 16-h photoperiod in a walk-in growth chamber (C5 Control System; Environmental Growth Chambers, Chagrin Falls, OH) with ADT of 23.0 ± 0.1 , 23.0 ± 0.1 , and 23.0 ± 0.1 °C for seasons I, II, and III, respectively. Air temperature, relative humidity, and carbon dioxide (CO_2) were measured and logged every 15 min by a data logger (DL1 Datalogger; Environmental Growth Chambers). Environmental data for the growth chamber environment are

reported in Table 2. Seedlings were irrigated with the same fertilizer used in the greenhouse environment.

Supplemental and sole-source lighting treatments. Seedlings in the greenhouse were grown under AL or AL supplemented with ≈ 70 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ *PPF* at plant height [as measured with a spectroradiometer (PS-100; Apogee Instruments, Inc., Logan, UT)] from 0600 to 2200 HR (Table 1) for 21 d (geranium and marigold) or 28 d (impatiens, petunia, and vinca). Supplemental light was delivered from either two 150-W HPS lamps (PL 2000; P.L. Light Systems Inc., Beamsville, Ontario, Canada), or eight 32-W LED arrays [120-cm long and 4-cm wide (Philips GreenPower LED production module; Koninklijke Philips Electronics N.V., The Netherlands)] spaced on 44.5-cm centers and 78.7 cm above the bench top providing (%) 87:13 red (664 nm): blue (466 nm) light (SL87:13). An automatic woven shade curtain (OLS 50; Ludvig Svensson Inc., Charlotte, NC) was retracted when the outdoor light intensity exceeded ≈ 1000 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ throughout the study to achieve a AL DLI of ≈ 6 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$.

Seedlings in the growth chamber were grown under a multilayer production system with SSL LEDs providing ≈ 185 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ *PPF* at plant height [as measured with a spectroradiometer (PS-100; StellarNet, Inc., Tampa, FL)] from 0600 to 2200 HR (Table 2) for the same duration as the plants in the greenhouse. Light was delivered from one of two LED arrays providing 87:13 red: blue light [SSL87:13 (Philips GreenPower LED production module)] spaced on 20.4-cm

Table 1. Average day and night plant canopy temperatures, relative humidity, and total daily light integral (DLI) under ambient solar daylight supplemented with ≈ 70 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ from high-pressure sodium (HPS) lamps or light-emitting diodes (LEDs; 87:13 red:blue light) from 0600 to 2200 HR. Impatiens, geranium, marigold, petunia, and vinca were placed under treatments on 1 Oct. 2013, 4 Nov. 2013, and 13 Jan. 2014.

Treatment initiation	Supplemental light source	Supplemental light ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	Total DLI ($\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)	Relative humidity (%)	Day canopy temp. (°C)	Night canopy temp. (°C)
1 Oct. 2013	Ambient	— ^a	6.6 ± 1.4	74.6 ± 22.0	20.5 ± 2.4	20.4 ± 1.9
	HPS	73.2 ± 34.6	10.6 ± 1.7		21.8 ± 1.7	21.7 ± 1.6
	LED	71.0 ± 13.4	10.5 ± 1.7		22.2 ± 1.9	22.2 ± 1.9
4 Nov. 2013	Ambient	—	6.3 ± 3.1	71.8 ± 15.3	19.1 ± 1.9	18.9 ± 1.8
	HPS	70.9 ± 28.4	10.4 ± 3.1		20.6 ± 1.4	20.4 ± 1.1
	LED	69.8 ± 12.6	10.3 ± 3.1		20.4 ± 1.4	20.4 ± 1.4
13 Jan. 2014	Ambient	—	6.7 ± 2.8	73.2 ± 15.3	18.5 ± 2.9	18.2 ± 2.7
	HPS	72.7 ± 30.0	10.9 ± 2.8		20.0 ± 2.0	19.9 ± 1.7
	LED	73.0 ± 10.4	10.9 ± 2.8		20.4 ± 1.9	20.3 ± 1.8

^aNo supplemental light provided.

Table 2. Average growth chamber daily light integral (DLI), relative humidity, carbon dioxide (CO_2), and sole-source light of ≈ 185 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ delivered from light-emitting diodes (LEDs) with varying proportions of red (R) and blue (B) light from 0600 to 2200 HR. Impatiens, geranium, marigold, petunia, and vinca were placed under treatments on 1 Oct. 2013, 4 Nov. 2013, and 13 Jan. 2014.

Treatment initiation	LED sole-source light	Light intensity ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	DLI ($\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)	Relative humidity (%)	CO_2 ($\mu\text{mol}\cdot\text{mol}^{-1}$)
1 Oct. 2013	87R:13B	184.6 ± 44.1	10.6	70.5 ± 6.6	491.7 ± 47.3
	70R:30B	185.7 ± 65.4	10.7		
4 Nov. 2013	87R:13B	183.2 ± 40.6	10.6	72.8 ± 4.5	497.9 ± 12.6
	70R:30B	183.5 ± 51.2	10.6		
13 Jan. 2014	87R:13B	184.1 ± 37.3	10.6	73.1 ± 4.6	507.6 ± 48.2
	70R:30B	181.6 ± 49.3	10.5		

centers or 70:30 red (660 nm):blue (455 nm) light (SSL70:30) [48.5-cm-long and 3.3-cm-wide (Philips GreenPower LED research module; Koninklijke Philips Electronics N.V.)] spaced on 7.6-cm centers. Three SSL87:13 LEDs or 16 SSL70:30 LEDs were mounted to stainless steel shelves (121-cm long and 61-cm wide). The shelves were composed of three vertical layers spaced 45.7 and 50.8 cm apart vertically for the 87:13 and 70:30 LEDs, respectively. Spectral quality of the SSL and SL were evaluated in nine positions at the beginning of each replication with a spectroradiometer (PS-100; StellarNet, Inc.) as shown in Figure 1.

Finishing culture and environment. At the end of greenhouse and growth chamber lighting treatments, 10 randomly selected seedlings from each tray were transplanted into 11.4-cm (600 mL) containers (Dillen Products, Middlefield, OH) filled with a commercial soilless medium composed of (by volume) 65% peat, 20% perlite, and 15% vermiculite (Fafard 2; Sun Gro Horticulture). Plants were placed in a common finish environment with a 16-h photoperiod of AL supplemented with a PPF of $\approx 70 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ from HPS lamps to provide a DLI of 11.2 ± 1.9 , 11.2 ± 2.6 , and $12.6 \pm 1.6 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ for seasons I, II, and III, respectively. Air temperatures in the finishing environment were 19.3 ± 2.3 , 19.2 ± 2.0 , and $19.3 \pm 1.8^\circ\text{C}$ for seasons I, II, and III, respectively. 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; Everris, Marysville, OH) to provide the following ($\text{mg}\cdot\text{L}^{-1}$): 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.

Data collection and calculations. At 21 d (geranium and marigold) or 28 d (impatiens, petunia, and vinca) after initiating SL and SSL treatments, 10 plants of each species were randomly selected and measured for height (measured from the base of the hypocotyl to the shoot apical meristem), leaf number, and stem diameter (measured above the lowest leaf with a digital caliper) (digiMax; Wiha, Schönnach, Germany). Total chlorophyll (a + b) content [i.e., relative chlorophyll content; (RCC)] was estimated using a SPAD chlorophyll meter (SPAD-502; Konica Minolta Sensing, Inc., Osaka, Japan). After non-destructive measurements were recorded, roots and shoots of all seedlings were separated and washed. All individual leaves were removed at the axil and leaf area was measured using a leaf area meter (LI-3100; LI-COR Inc., Lincoln, NE). Roots and shoots (leaves and stems) were placed in a drying oven at 70°C for at least 4 d, and then RDM and SDM were recorded. The sturdiness quotient (SQ) was calculated as (stem diameter/stem length). The quality index (QI), an objective, integrated, and quantitative measurement of quality, was calculated as the [total dry mass $\times$ (shoot:root ratio + sturdiness quotient)] (Currey et al., 2013).

Plants in the finish environment were monitored daily following transplant. When the first flower was fully reflexed, the date, number of nodes beneath the first open flower, and plant height from the surface of the medium to the top of the plant were recorded. Time to flower (TTF) was

calculated as the time from transplant into the finish environment to the first open flower.

Statistical analysis. The experiment used a complete block design, replicated over three seasons for each of the five species. Effects of light treatments were compared by ANOVA using SAS (SAS version 9.3; SAS Institute, Cary, NC) PROC MIXED with an additional program (Arnold M. Saxton, University of Tennessee, Knoxville, TN) that provided pairwise comparisons between treatments using Tukey's honestly significant test at $P \leq 0.05$.

Results

Morphology. Height of all species was significantly influenced by both SL and SSL (Fig. 2A and B). Vinca and impatiens were generally taller under SL and SSL than under AL. For instance, height of impatiens seedlings under AL was 29%, 18%, 26%, and 13% shorter compared with those under HPS, SL87:13, SSL87:13 and SSL70:30, respectively. Height of geranium, petunia, and marigold seedlings grown under SSL87:13 and SSL70:30 LEDs was suppressed by 21% and 26%, 75% and 79%, and 18% and 16%, respectively, compared with those under HPS lamps. Stem diameter of all species with the exception of petunia was influenced by SL and SSL (Fig. 2C and D). For example, under SL and SSL, stem diameter of vinca, impatiens, and geranium was 12% to 17%, 26% to 45%, and 8% to 15% greater, respectively, compared with those seedlings under AL. Stem diameter of marigold seedlings was 17% and 13% greater under SL from HPS and SL87:13 LEDs, respectively, compared with AL. Leaf number of all species was significantly influenced by SL and SSL (data not presented). For instance, leaf number of vinca, geranium, and marigold was 40% to 50%, 9% to 31%, and 19% to 21% greater, respectively, for seedlings grown under HPS, SL87:13, SSL87:13, and SSL70:30 LEDs compared with AL. Leaf number of impatiens and petunia was 26% to 34% and 32% to 62% greater for seedlings grown under SL or SSL, respectively, compared with AL. Total leaf area of all species generally increased under SL and SSL (Fig. 2E and F). Leaf area of vinca and impatiens seedlings was 20% to 134% and 21% to 75% greater for those grown under SSL87:13 LEDs compared with the other treatments, respectively. Leaf area of geranium was 49%, 20%, and 24% greater for seedlings grown under HPS lamps compared with those under AL, SSL87:13, and SSL70:30 LEDs, respectively.

Physiology. Relative chlorophyll content of all species was significantly greater under SL and SSL (Fig. 2G and H). The RCC of impatiens, geranium, and petunia seedlings under SSL70:30 LEDs was 22% to 47%, 4% to 21%, and 44% to 85% greater, respectively, compared with those under AL, HPS and SL87:13 LEDs. For marigold, RCC was greatest under SL and SSL LEDs compared with HPS lamps or AL.

Fig. 1. Spectral quality of $70 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ delivered from supplemental (SL) high-pressure sodium (HPS) lamps and light-emitting diodes (LEDs) with (%) 87:13 red:blue light in the greenhouse or $185 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ delivered from sole-source (SSL) LEDs with 87:13 or 70:30 red:blue light in a growth chamber.

Fig. 2. (A–H) Effect of ambient light (AL); or $70 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ of supplemental light (SL) delivered from high-pressure sodium (HPS) lamps or light-emitting diodes [LEDs; SL87:13 (%) red:blue light]; or $185 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ of sole-source (SSL) light delivered from LEDs [SSL87:13 and SSL70:30 (%) red:blue light] during seedling production on height, stem diameter, relative chlorophyll content (SPAD), and leaf area of vinca, impatiens, geranium, petunia, and marigold after 21 or 28 d. Different lowercase letters above each light source within a species are significantly different by Tukey's honestly significant difference test at $P \leq 0.05$. Each bar represents a mean of 10 plants, and error bars represent SEM of the mean.

Growth. Root dry mass (RDM) of all species was generally higher under SL and SSL treatments (Fig. 3A and B). For example, RDM of vinca, impatiens, and geranium was 104% and 101%, 81% and 93%, and 102% and 109% greater for seedlings grown under HPS lamps and SSL87:13 LEDs, respectively, compared with AL. Root dry mass of petunia was 41% to 57% greater under SSL LEDs compared with SL. Marigold RDM increased 140% to 260% under SL and SSL. Shoot dry mass of all species was significantly greater under SL and SSL (Fig. 3C and D). For example, SDM of vinca, impatiens, geranium, petunia, and marigold was 74% to 154%, 64% to 164%, 50% to 82%, 62% to 72%, and 59% to 161% greater under SL or SSL, respectively, compared with AL. Additionally, SDM of vinca and impatiens seedlings was 23% to 46% and 21% to 61% higher, respectively, under SSL than SL.

Quality. Light treatments significantly influenced the SQ of all species differently (Fig. 3E and F). However, the SQ of impatiens, geranium, petunia, and marigold were generally similar when seedlings were propagated under AL or HPS lamps. For example, the SQ of geranium increased by 36% and 30% under SSL70:30 LEDs compared with seedlings under AL and HPS lamps, respectively. The SQ of petunia was 133% to 306% greater for seedlings grown under SSL LEDs, respectively, compared with those under AL and SL. The QI increased differently for all species under SL and SSL (Fig. 3G and H). For example, the QI of vinca was 117% higher for seedlings grown under HPS lamps compared with AL; however, for petunia it increased by 106% and 129% for seedlings grown under SSL87:13 and SSL70:30 LEDs, respectively, compared with AL.

Flowering. Generally, TTF was significantly reduced when seedlings were grown under SL or SSL for all species with the exception of impatiens (Fig. 4A and B). Time to flower of impatiens seedlings grown under SSL87:13 LEDs was delayed by 8 to 11 d compared with those grown under AL, SL, and SSL70:30. Height at flower of all species with the exception of impatiens and marigold was significantly influenced by SL and SSL received as a seedling (Fig. 4C and D). For example, height at flower of vinca and petunia was reduced by 50% and 25% when seedlings were grown under SSL70:30 LEDs, respectively, compared with those under AL. The number of nodes below the first open flower was affected differently by the lighting treatment received as a seedling for all species, with the exception of marigold and petunia (Fig. 4E and F). For instance, the average number of nodes at flower for impatiens was reduced by two under AL, compared with the SSL87:13 LEDs. Additionally, vinca and geranium had an average of one less node when seedlings were grown under SSL70:30 LEDs compared with AL.

Discussion

Without SL, young plants are grown under a mean DLI of 6 to 8 mol·m⁻²·d⁻¹ at latitudes of 35 to 45°N during peak production in January and February (Korczynski et al., 2002). To produce high-quality young plants, greenhouse growers try to maintain the recommended DLI of 10 to 12 mol·m⁻²·d⁻¹ (Runkle, 2007) by providing SL with a PPF of 50 to 80 μmol·m⁻²·s⁻¹ from HPS lamps (Fisher and Runkle, 2004). Therefore, we selected 70 μmol·m⁻²·s⁻¹ as our target for SL to achieve a supplemental DLI of ≈4 mol·m⁻²·d⁻¹.

Previous research has shown that bedding plant seedlings were generally more compact with a larger stem diameter, higher SQ, and higher RCC under LED SL providing a red:blue light ratio (%) of 85:15 and 70:30 (Randall and Lopez, 2014). In addition, Wollaeger and Runkle (2013) determined that there were no consistent differences in plant growth when bedding plant seedlings were grown under LED SSL providing orange, red, or hyper-red light. They also suggested that hyper-red LEDs could be selected over red LEDs as they were 7% more efficient; the efficiency (μmol·J⁻¹) of the orange, red, or hyper-red LEDs was 0.72, 2.29, and 2.46, respectively. Previous studies have also reported that high-intensity SL or SSL containing blue light generally inhibit stem elongation when added to red light (Heo et al., 2003; Randall and Lopez, 2014; Wollaeger and Runkle, 2014). For example, blue light and a combination of blue and red light resulted in a shorter peduncle length of cyclamen (*Cyclamen persicum* 'Dixie White') than red light alone (Heo et al., 2003) and more compact bedding plant seedlings with a combination of red and blue light (Randall and Lopez, 2014; Wollaeger and Runkle, 2014). Thus, we selected commercially available LED arrays that provided a light ratio of 87:13 red (peak = 664 nm):blue (peak = 466 nm) light for our SL and SSL. Therefore, the primary objective of our experiment was to quantify and compare the growth, morphology, quality, and subsequent development of seedlings grown under AL, AL plus SL, and SSL while all other environmental characteristics, including temperature, humidity, and DLI were constant.

In order for young plants to withstand shipping and mechanical transplanting (Latimer, 1998), they must be compact (reduced leaf area and height) and fully rooted with a large stem diameter and high RDM (Pramuk and Runkle, 2005; Wollaeger and Runkle, 2014). The QI is a tool that integrates morphological parameters such as dry mass, stem length, and diameter that contribute to a high-quality seedling. Geranium, petunia, and marigold seedlings grown under SSL were generally more compact, darker in foliage color (higher RCC), and had a higher RDM and QI than those grown in the greenhouse under AL or SL. Previous studies have determined that the QI of young plants increases as DLI increases (Currey et al., 2012,

2013; Randall and Lopez, 2014). For example, as the DLI increased from 1.2 to 12.3 mol·m⁻²·d⁻¹, the QI of diascia (*Diascia barberae* 'Wink Coral') and lantana (*Lantana camara* 'Lucky Gold') rooted cuttings increased 960% and 53%, respectively (Currey et al., 2013). Similarly, the QI of all species in the current study was greater under both SL and SSL with a DLI of ≈10.6 mol·m⁻²·d⁻¹ compared with seedlings under AL with a DLI of ≈6.5 mol·m⁻²·d⁻¹; and the QI of impatiens, geranium, and petunia was similar or greater for seedlings grown under SSL compared with SL.

Leaf area of all species in the current study was generally similar or greater under SL compared with AL, and under SSL treatments compared with SL. However, under SSL, as the percentage of blue light increased from 13% to 30%, leaf area generally decreased. Previous studies have reported that plants under red light typically have greater leaf area than those grown under ≥13% blue, or only blue light (Son and Oh, 2013; Wollaeger and Runkle, 2014). For example, leaf area of lettuce (*Lactuca sativa* 'Sunmang' and 'Grand Rapid TBR') increased by 325% and 324%, respectively, as the (%) of red light from LED SSL providing 171 μmol·m⁻²·s⁻¹ increased from a ratio of 41:59 to 100:0 red:blue light (Son and Oh, 2013). Wollaeger and Runkle (2013) reported that total leaf area of impatiens 'SuperElfin XP Red' and petunia 'Wave Pink' seedlings grown under SSL LEDs providing a red:blue light ratio (%) of 100:0 was 55% to 114% and 57% to 130% greater, respectively, than seedlings grown under 25% or greater blue light. Generally, a smaller leaf area is desired in ornamental young plant production as seedlings and cuttings are grown under a dense and competitive environment that can induce excessive stem extension due to the shade avoidance response.

Additionally, studies have also reported leaf anatomical changes with the addition of blue light (Sæbø et al., 1995; Schuerger et al., 1997). For example, leaf thickness of pepper plants (*Capsicum annuum*) increased when grown under SSL providing blue light from blue fluorescent lamps providing a red:far-red:blue ratio (%) of 98:1:1 compared with those providing a red:far-red ratio of 99:0 or 83:17. Therefore, we can hypothesize that blue light promotes an increase in leaf thickness and a reduction in leaf area. However, the extent to which blue light affects plant growth and morphology across species is not fully understood.

Relative chlorophyll content generally increased for all species investigated as the amount of blue light increased from 7% for HPS lamps to 30% for SSL70:30 LEDs. Similarly, Son and Oh (2013) reported that RCC of lettuce 'Sunmang' and 'Grand Rapid TBR' increased by ≈140% and ≈150% as the percentage of SSL blue light increased from a red:blue light ratio (%) of 100:0 to 53:47 and 100:0 to 74:26, respectively. However, chlorophyll concentration of impatiens

Fig. 3. (A–H) Effect of ambient light (AL); or 70 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ of supplemental light (SL) delivered from high-pressure sodium (HPS) lamps or light-emitting diodes [LEDs; SL87:13 (%) red:blue light]; or 185 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ of sole-source (SSL) light delivered from LEDs [SSL87:13 and SSL70:30 (%) red:blue light] during seedling production on root dry mass, shoot dry mass, sturdiness quotient, and quality index of vinca, impatiens, geranium, petunia, and marigold after 21 or 28 d. Different lowercase letters above each light source within a species are significantly different by Tukey's honestly significant difference test at $P \leq 0.05$. Each bar represents a mean of 10 plants, and error bars represent SES of the mean.

Fig. 4. (A–F) Effect of ambient light (AL); or $70 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ of supplemental light (SL) delivered from high-pressure sodium (HPS) lamps or light-emitting diodes [LEDs; SL87:13 (%) red:blue light]; or $185 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ of sole-source (SSL) light delivered from LEDs [SSL87:13 and SSL70:30 (%) red:blue light] during seedling production on finish time to flower, height at flower, and nodes below flower of vinca, impatiens, geranium, petunia, and marigold after 21 or 28 d. Different lowercase letters above each light source within a species are significantly different by Tukey's honestly significant difference test at $P \leq 0.05$. Each bar represents a mean of 10 plants, and error bars represent SES of the mean.

and petunia seedlings was not influenced by SSL treatments providing anywhere from a red:blue light ratio (%) of 0:100 to 100:0 (Wollaeger and Runkle, 2014). Although we did not determine anthocyanin content, visually, geranium seedling leaves under SSL had much darker patterns, especially under SSL70:30 LEDs (Fig. 5A and C). Marigold under SSL developed dark-purple spotting on

the adaxial and abaxial surface of leaves and the severity appeared to increase as the percentage of blue light increased from 13% to 30% (Fig. 5B). Similarly, when marigold 'Deep Orange' was grown under SSL providing a blue:green light ratio (%) 10:10 with the remaining percentages of orange:red:hyper-red light 20:30:30, 0:80:0, 0:60:20, 0:40:40, 0:20:60, and 0:0:80, seedlings

developed a similar leaf disorder on the abaxial surface of the leaves (Wollaeger and Runkle, 2013). Previous studies have reported that certain crops grown under ultraviolet radiation, blue light, or far-red light deficient environments or red dominant environments have developed leaf disorders such as edema or intumescence. Further research would have to be conducted to

Fig. 5. (A) Plug trays of geranium seedlings grown under ambient light, $70 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ of SL delivered from high-pressure sodium (HPS) lamps, light-emitting diodes (LEDs) providing a red:blue light ratio (%) of 87:13, sole-source LEDs providing a red:blue light ratio (%) of 87:13 and 70:30 from left to right. (B) Dark-purple pattern on geranium leaves under LED sole-source lighting (SSL) providing a red:blue light ratio (%) of 70:30. (C) Dark-purple spotting on the adaxial and abaxial surface of French marigold leaves under SSL.

determine the exact cause of the purple spotting.

Previous studies have reported that as DLI increases during the young plant stage, subsequent TTF decreases (Currey et al., 2012; Lopez and Runkle, 2008; Oh et al., 2010). In the current study, vinca and geranium were the only species that flowered faster when grown as a seedling under either SL or SSL providing a higher DLI compared with AL. Interestingly, TTF of impatiens (day neutral flowering response) seedlings grown under SSL87:13 LEDs was delayed up to 11 d compared with those grown under AL, SL, or SSL30:70 LEDs. When the amount of blue light was increased by 17% ($\approx 31 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) in the SSL30:70 LEDs, TTF was reduced by 8 d. Similarly, Wollaeger and Runkle (2014) reported that impatiens

‘SuperElfin XP Red’ grown under LED SSL without blue light had the fewest flower buds after 4 weeks and thus a delay in TTF. They postulated that an accelerated flowering response such as an increase in flower buds with increasing blue light could be attributed to *CRY2* cryptochrome activity. For example, *CRY2* degradation regulates photoperiodic flowering response and acts on downstream genes, including *CO* and *FT* (Chaves et al., 2011; El-Assal et al., 2003). Additionally, Meng (2014) reported that night interruption lighting with high intensity blue light, alone and when added to red and far-red light, can regulate flowering of photoperiodic crops.

Conclusions

Supplemental and SSL with blue light suppress extension growth and leaf expansion, resulting in compact young plants, which is often a desirable characteristic for greenhouse growers (Randall and Lopez, 2014; Wollaeger and Runkle, 2013, 2014). In addition, LEDs could be used for SSL in high-density multilayer production systems as an effective alternative to greenhouse production systems for annual bedding plant seedling production. From the results of our study and that of Wollaeger and Runkle (2014), a general recommendation for SSL of bedding plant seedlings would be to include anywhere from 10% to 30% blue light depending on the desired crop-specific attributes and costs. Further research is necessary to determine the effects of far-red light in addition to sole-source red and blue light on growth, morphology, quality, and subsequent flowering of day neutral and photoperiodic bedding plant seedlings.

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