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Cuttings of *Impatiens*, *Pelargonium*, and *Petunia* Propagated under Light-emitting Diodes and High-pressure Sodium Lamps Have Comparable Growth, Morphology, Gas Exchange, and Post-transplant Performance

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Abstract. **Increasing photosynthetic daily light integral (DLI) by supplementing with high-pressure sodium (HPS) lamps during propagation has been shown to enhance photosynthesis and biomass accumulation of cuttings. The development of high-intensity light-emitting diodes (LEDs) is a promising technology with potential as a greenhouse supplemental lighting source. Our objective was to quantify the impact of narrow spectra supplemental lighting from LEDs on growth, morphology, and gas exchange of cuttings compared with traditional HPS supplemental lighting. Cuttings of *Impatiens hawkeri* W. Bull 'Celebrette Frost', *Pelargonium* ×*hortorum* L.H. Bailey 'Designer Bright Red', and *Petunia* ×*hybrida* Vilm. 'Suncatcher Midnight Blue' were received from a commercial propagator and propagated in a glass-glazed greenhouse at 23 °C air and substrate temperature set points. After callusing (≈5 mol·m^{-2}·d^{-1} for 7 days), cuttings were placed under 70 μmol·m^{-2}·s^{-1} delivered from HPS lamps or LED arrays with varying proportions (%) of red:blue light (100:0, 85:15, or 70:30). After 14 days under supplemental lighting treatments, growth, morphology, and gas exchange of rooted cuttings were measured. There were no significant differences among *Impatiens* and *Pelargonium* cuttings grown under different supplemental light sources. However, compared with cuttings propagated under HPS lamps, stem length of *Petunia* cuttings grown under 100:0 red:blue LEDs was 11% shorter, whereas leaf dry mass, root dry mass, root mass ratios, and root:shoot ratio of cuttings grown under 70:30 red:blue LEDs were 15%, 36%, 17%, and 24% higher, respectively. Supplemental light source had minimal impact on plants after transplant. Our data suggest that LEDs are suitable replacements for HPS lamps as supplemental light sources during cutting propagation.**

Stem-tip cuttings of vegetatively propagated annual bedding plants are frequently propagated in late winter and early spring to meet the spring and early summer market demand for flowering bedding plants. However, this is also when seasonally low ambient outdoor DLIs (Korczynski et al., 2002) are further reduced inside a greenhouse by glazing material, interior structures, and hanging baskets suspended above benches (Faust, 2004; Hanan, 1998). Increasing DLI during propagation has been shown to enhance photosynthesis (P_n), growth, dry mass accumulation, and quality of rooted cuttings and reduce time to flower of transplanted cuttings (Currey et al., 2012; Currey and Lopez, 2012; Hutchinson et al., 2012; Lopez and Runkle, 2008). Whereas maintaining clean glazing material, minimizing superstructure, and reducing the density of hanging baskets may increase greenhouse DLI, the only way to appreciably increase DLI is to provide supplemental lighting.

There are several considerations when evaluating sources for providing supplemental light in a greenhouse, including light intensity, spectrum, electrical consumption, and uniformity of lighting patterns as well as financial considerations such as initial and ongoing maintenance costs measured with respect to return on investment (Sherrard, 2011). The most common supplemental light sources currently used in greenhouse production worldwide are high-intensity discharge (HID) HPS lamps, and several characteristics of HPS contribute to their popularity (Fisher and Both, 2004; Nelson, 2012; Sherrard, 2011; Spaargren, 2001). The majority of light emitted from HPS lamps is in the range of 565 to 700 nm, primarily yellow (565 to 590 nm) and orange (590 to 625 nm), with a peak at 589 nm. The efficiency for HPS lights is ≈25% to 30% and the lifespan for a lamp is 10,000 to 12,000 luminous h. However, up to 70% to 75% of the energy not converted to photosynthetic light is emitted as radiant heat, and the high surface temperature of HPS bulbs (up to 450 °C) necessitates adequate separation or distance between lamps and plants to avoid leaf scorch.

LEDs are solid-state, semiconducting diodes that can emit light from ≈250 nm to 1000 nm or greater (Bourget, 2008). Although low-intensity LEDs have been used for several decades for electronic applications, the development of LEDs with an output of 1 W or greater create the potential to use aggregates of LEDs (arrays) as supplemental photosynthetic light sources. There are several features of LEDs that make them attractive alternatives to HPS lamps. The most unique aspect of LEDs is the availability of narrow-spectrum light at wavebands of primary interest for plant growth and development, including blue (450 nm), red (660 nm), and far-red (730 nm). Additionally, LEDs currently have a luminous efficiency of 38% (red) to 50% (blue) in converting energy to light (M. Bourget, personal communication) and an estimated life of 50,000 luminous h or greater (Bourget, 2008) with increases in efficiency and lifespan occurring as technologies advance. The interest in the use of LEDs is increasing in commercial plant production, yet the impact of and science underlying the use of LEDs as a supplemental light source in ornamental plant propagation and production are not clear.

The narrow spectra of supplemental LED lighting have potential implications on morphology, development, and gas exchange of plants. First, although all photons between 400 and 700 nm (photosynthetically active radiation) are effective in driving photosynthesis, not all photons are equally efficient in their photosynthetic yield with two distinct broad peaks in the blue (400 to 500 nm) and red (600 to 700 nm) ranges (McCree, 1972). Therefore, the variation in relative quantum efficiency in the spectra of a supplemental light source may affect the efficacy of the light source in enhancing biomass accumulation. Additionally, there are several photoreceptors in higher plants such as phytochrome, cryptochrome, and phototropins that absorb

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specific wavelengths and mediate physiological responses (Briggs et al., 2006; Cashmore, 2006; Sharrock and Matthews, 2006). For example, the ratio of phytochrome in the physiologically active far red state (P_{fr}) to total phytochrome [P_{fr} + red phytochrome (P_r)] influences the magnitude of the shade avoidance response (i.e., stem elongation) for shade-intolerant species as well as flowering of photoperiodic plants with a long-day requirement for flowering (Glover, 2007; Thomas and Vince-Prue, 1997). Additionally, cryptochromes are blue light receptors that influence stem elongation.

Previous studies have focused on the use of LEDs as a sole light source in highly controlled and enclosed environments (Massa et al., 2008) or as a supplemental light source for overhead (Dueck et al., 2012) or intracanopy (Dueck et al., 2006; Hovi-Pekkanen et al., 2006; Trouwborst et al., 2010) lighting for greenhouse vegetable production. Furthermore, Currey et al. (2012) and Lopez and Runkle (2008) have reported the use of supplemental light to increase the DLI during root development of cuttings in propagation. However, little is known about the effects of supplemental light source and quality on growth, morphology, and gas exchange during vegetative propagation of herbaceous cuttings with special reference to narrow-spectra high-intensity LEDs. Our objective in the present study was to quantify the impact of supplemental light provided by LEDs or HPS lamps during root development of cuttings during propagation.

Materials and Methods

Plant material, culture, propagation environment. On 18 Jan., 24 Feb., and 12 Apr. 2012, ≈200 cuttings each of *Impatiens hawkeri* 'Celebrette Frost', *Pelargonium* × *hortorum* 'Designer Bright Red', and *Petunia* × *hybrida* 'Suncatcher Midnight Blue' were received at Purdue University, West Lafayette, IN (lat. 40° N). Cuttings were placed in 105-cell propagation trays (28-mL individual cell volume; T.O. Plastics, Inc., Clearwater, MN) filled with a propagation substrate composed of (v/v) two parts soilless substrate (Fafard 1P; Fafard, Inc., Agawam, MA) and one part coarse perlite (Strong-Lite Coarse Perlite; Sun Gro Horticulture, Bellevue, WA). Cuttings were sprayed to runoff with a solution containing 300 mg·L^{-1} non-ionic surfactant (Cap-Sil; Aquatrols, Paulsboro, NJ) so that water would not accumulate on the plant foliage.

All cuttings were placed in a glass-glazed greenhouse under a 16-h photoperiod consisting of natural daylengths with day-extension lighting from HPS lamps (e-system HID; PARSource, Petaluma, CA) that delivered a supplemental photosynthetic photon flux (*PPF*) of ≈30 μmol·m^{-2}·s^{-1} at plant height [as measured with a quantum sensor (LI-COR Biosciences, Lincoln, NE)] when outdoor irradiance was less than 250 μmol·m^{-2}·s^{-1} from 0600 to 2200 HR. The air and substrate temperature set points of 23 ± 1 °C and a DLI maintained at ≈5 mol·m^{-2}·d^{-1} for callusing. Resistance-based sensors (External Temperature Sensor; Spectrum Technologies, Inc., Plainfield, IL) recorded air and substrate temperatures every 30 s and averages were logged every 15 min by a data logger (Watchdog 2800 Weather Station; Spectrum Technologies, Inc.). Amplified quantum sensors (SQ-212; Apogee Instruments, Inc., Logan, UT) measured solar *PPF* every 30 s under each light treatment, and the average of each sensor was logged every 15 min by a data logger (Watchdog 2800 Weather Station; Spectrum Technologies, Inc.). Environmental data during callusing are reported in Table 1.

Supplemental lighting treatments and culture. After 7 d of callusing, 70 cuttings of each species were placed under ambient daylight supplemented with a *PPF* of ≈70 μmol·m^{-2}·s^{-1} at plant height [as measured with a spectroradiometer (PS-300; Apogee Instruments)] from 2000 to 2200 HR (Table 2). Supplemental light was delivered from a 150-W HPS lamp (PL2000; P.L. Lights, Beamsville, Ontario, Canada) or one of three LED arrays (Orbital Technologies Corporation, Madison, WI) varying in the proportion (%) of red:blue light. Each LED array consisted of bars containing 24 627-nm or 450-nm LEDs. Each array consisted of seven 1.88-cm square, 1.22-m long, and 1.3-mm wide, hollow aluminum bars with seven red (100:0 red:blue) or four red and three blue (85:15 and 70:30 red:blue) bars alternating spaced on 22-cm centers across a 1.82-m bar. Each bar was cooled with a single 3.6-W axial blower mounted on the end of each bar.

Spectral scans of supplemental light were taken at night with a spectroradiometer (PS-300; Apogee Instruments, Inc.). Spectral quality of supplemental light sources is shown in Figure 1. Air and substrate temperature and ambient light for each supplemental light treatment were measured as previously described and are reported in Table 2. Power use for both HPS lamps and LED lights were measured using a plug power meter (P440 Kill A Watt; P3 International, New York, NY).

Immediately after cuttings were placed in substrate, mist was applied consisting of tap water supplemented with a complete water-soluble fertilizer (Jack's LX 16N–0.94P–12.3K Plug Formula for High Alkalinity Water; J.R. Peters, Inc., Allentown, PA) and micronutrient supplement (Compound 111; Scotts Co., Marysville, OH) providing (in mg·L^{-1}) with each misting event: 60 nitrogen (N), 6 phosphorus (P), 47 potassium (K), 11 calcium (Ca), 6.24 magnesium (Mg), 0.25 boron (B), 0.12 copper (Cu), 1.53 iron (Fe), 0.35 manganese (Mn), 0.09 molybdenum (Mo), and 0.21 zinc (Zn). Six d after transfer of cuttings under lighting treatments, misting frequency was reduced to once every 30 min beginning and ending 2 h before and after the photoperiod, respectively; 8 d after cutting transfer, misting was reduced to begin and end 1 h before and after the photoperiod.

Ten d after the placement of cuttings under DLI treatments, the use of mist was discontinued and cuttings were hand-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; The Scotts Co.) to provide the following (in mg·L^{-1}): 200 N, 26 P, 163 K, 50 Ca, 20 Mg, 1.0 Fe, 0.50 Mn and Zn, 0.24 Cu and B, and 0.10 Mo. Irrigation water was supplemented with 93% sulfuric acid (Brenntag, Reading, PA) at 0.08 mL·L^{-1} to reduce alkalinity to 100 mg·L^{-1} and pH to a range of 5.8 to 6.2. Environmental data under each treatment were measured as previously described and are reported in Table 2.

Forcing culture and environment. Fifteen rooted cuttings of each species from each supplemental lighting treatment were planted in 11.4-cm-diameter plastic containers (651-mL volume; Landmark Plastics, Akron, OH) filled with a soilless substrate (Fafard C1-P; Fafard, Inc.). Plants were grown under ambient light supplemented with a *PPF* of ≈100 μmol·m^{-2}·s^{-1} at plant height [as measured with a line quantum sensor (LI-COR Biosciences)], respectively, from 2000 to 2200 HR delivered from 1000-W HPS lamps (e-system HID; PARSource). The greenhouse air temperature set point was a constant 21 °C. Environmental data during forcing were measured as previously described and are reported in Table 3. Substrate pH and electrical conductivity (EC) were measured weekly using the pour-through method to ensure substrate pH and EC were maintained within published recommended ranges (Whipker et al., 2011a, 2011b).

Data collection and calculations. Chlorophyll fluorescence of 10 cuttings per treatment was measured on the adaxial epidermis of the most fully expanded leaf using a portable chlorophyll fluorescence system (Plant Efficiency Analyzer; Hansatech Instruments Ltd., Norfolk, U.K.) 14 d after cuttings were placed under supplemental light treatments. Leaves were dark-acclimated for 1200 s within the manufacturer's plastic and foam clips before measurements were recorded. Fluorescence was measured by opening the shutter clip and exposing the leaf for 5 s to light with a peak wavelength of 650 nm that was provided at 3000 μmol·m^{-2}·s^{-1} to saturate PS II. Chlorophyll fluorescence was expressed as chlorophyll fluorescence (F_v/F_m).

Table 1. Average daily greenhouse air and substrate temperatures and daily light integral (DLI) during callusing before being placed under supplemental lighting treatments.

	Temperature (°C)		
Propagation date	Air	Substrate	DLI (mol·m^{-2}·d^{-1})
18 Jan.	22.2 ± 0.6	22.2 ± 0.8	4.4 ± 0.4
28 Feb.	22.1 ± 0.8	22.8 ± 0.1	4.3 ± 1.5
12 Apr.	22.3 ± 0.5	22.6 ± 0.7	5.5 ± 1.8

Table 2. Average daily greenhouse air and substrate temperatures and daily light integral (DLI) during root development of *Impatiens*, *Pelargonium*, and *Petunia* grown under ambient daylight supplemented with ≈70 μmol·m^{-2}·s^{-1}, respectively, delivered from high-pressure sodium (HPS) lamps or light-emitting diodes with varying proportions of red:blue light from 2000 to 2200 HR.

Propagation date	Supplemental light source	Supplemental light (μmol·m^{-2}·s^{-1})	Supplemental DLI (mol·m^{-2}·d^{-1})	Ambient DLI (mol·m^{-2}·d^{-1})	Temperature (°C)	
					Air	Substrate
18 Jan.	HPS	70.1 ± 10.7	4.0	3.5 ± 1.0	23.6 ± 1.2	22.3 ± 0.4
	100:0	70.0 ± 11.1	4.0	3.5 ± 0.9	23.8 ± 0.4	23.6 ± 0.7
	85:15	70.2 ± 10.4	4.0	4.5 ± 1.5	22.8 ± 0.7	22.4 ± 0.7
	70:30	71.2 ± 10.6	4.1	5.4 ± 1.3	24.1 ± 0.3	n/a
24 Feb.	HPS	70.8 ± 17.2	4.1	5.3 ± 1.2	24.3 ± 1.4	23.7 ± 0.8
	100:0	70.7 ± 11.5	4.1	5.6 ± 1.1	23.5 ± 1.6	23.8 ± 0.7
	85:15	71.6 ± 8.8	4.1	5.1 ± 1.9	24.8 ± 1.1	23.0 ± 1.1
	70:30	68.9 ± 9.2	4.0	5.8 ± 1.9	24.4 ± 1.3	23.8 ± 0.7
12 Apr.	HPS	70.9 ± 14.0	4.1	4.9 ± 2.1	22.9 ± 0.8	22.5 ± 1.0
	100:0	71.1 ± 10.2	4.1	4.3 ± 1.6	23.3 ± 1.0	21.9 ± 0.7
	85:15	69.2 ± 12.4	4.0	4.9 ± 2.1	22.8 ± 1.4	22.5 ± 0.4
	70:30	69.3 ± 15.4	4.0	4.5 ± 2.0	23.3 ± 1.3	22.9 ± 0.9

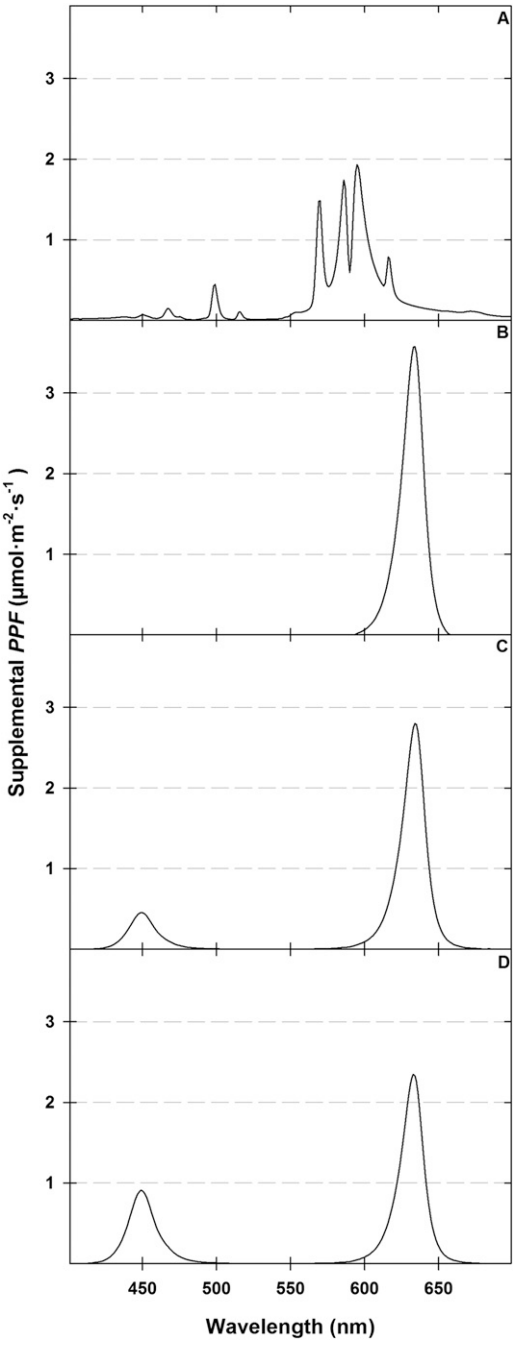

Fig. 1. (**A**–**D**) Spectral quality of 70 μmol·m^{-2}·s^{-1} delivered from high-pressure sodium (HPS) lamps (**A**) or light-emitting diodes (LEDs) with (%) 100:0 (**B**), 85:15 (**C**), or 70:30 (**D**) red:blue light.

Photosynthetic light-response curve measurements were performed in the greenhouse between 0900 and 1300 HR and were organized by sample across replication and time to reduce time-of-day effects. Measurements were conducted 13, 14, and 15 d after placing cuttings under supplemental light treatments with a portable photosynthesis system (LI-6400XT; LI-COR Biosciences) fitted to a 6-cm^2 leaf chamber with a LED light source (6400-02B; red at 665 nm and blue at 470 nm) providing a *PPF* of 0, 15, 30, 45, 60, 75, 100, 250, 500, 1000, 1250, and 1500 μmol·m^{-2}·s^{-1}. The reference CO_2 concentration inside the leaf chamber was 400 μmol·mol^{-1} and the flow of air into the chamber was set to maintain a constant mole fraction of 8.0 mmol of water inside the chamber. Leaf temperature inside the leaf chamber was maintained at 23.0 °C with dual Peltier devices that heated or cooled the air circulating through the chamber. Leaf area for leaves not covering the entire 6-cm^2 chamber area was adjusted by excising sample tissue immediately after measurements were recorded and leaf area was determined by scanning the leaf through a leaf-area meter (LI-3000; LI-COR Biosciences).

Survey P_n, transpiration (E) and stomatal conductance (g_S) measurements were performed in the greenhouse between 0900 and 1300 HR and, like with light curve measurements, were organized by sample across replication and time to reduce time-of-day effects. Measurements were conducted 14 d after placing cuttings under supplemental light treatments with a portable photosynthesis system (LI-6400XT; LI-COR Biosciences) fitted to a 6-cm^2 opaque plastic leaf chamber. The reference CO_2 concentration, flow of air, and leaf temperature inside the chamber were 400 μmol·mol^{-1}, 8.0 mmol, and 23.0 °C, respectively. Immediately after measurements were recorded, leaves inside the chamber were excised and leaf area of sampled tissue was determined as previously described.

Light response curves were fitted using the model described by Nemali and Van Iersel (2004):

$$P_n = P_{gmax}\,(1 - e^{-\infty \times PPF/Pgmax}) - R_d, \quad [1]$$

where P_{gmax} is maximum gross photosynthesis, ∞ is quantum use efficiency, and dark

Table 3. Average daily greenhouse air and substrate temperatures and daily light integral (DLI) during finishing.

Propagation date	Temperature (°C)	DLI ($mol \cdot m^{-2} \cdot d^{-1}$)
18 Jan.	21.3 ± 0.9	11.6 ± 5.4
24 Feb.	21.5 ± 1.2	14.3 ± 3.1
12 Apr.	22.9 ± 2.2	14.6 ± 3.8

Table 4. Analyses of variance for the effect of supplemental light source (S) and replication (R) on cutting growth and morphology.

	Impatiens		*Pelargonium*		*Petunia*	
Data	S	R	S	R	S	R
Stem length	NS[z]	***	NS	***	*	***
Stem caliper	NS	***	NS	***	NS	***
Node number	NS	*	NS	NS	NS	***
Leaf dry mass	NS	***	NS	***	**	***
Root dry mass	NS	***	NS	***	***	***
Stem dry mass	NS	***	NS	***	NS	NS
Leaf mass ratio	NS	***	NS	NS	NS	***
Root mass ratio	NS	***	NS	***	***	**
Stem mass ratio	NS	***	NS	NS	NS	NS
Root:shoot ratio	NS	***	NS	***	***	**
Leaf area	NS	***	NS	*	NS	NS
Leaf area ratio	NS	NS	NS	NS	NS	NS
Specific leaf area	NS	***	NS	*	NS	NS

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

respiration (R_d). Light compensation point (LCP) and light saturation point (LSP) were determined by solving for $P_n = R_d$ and $P_n = P_{gmax} \times 0.95$, respectively.

Cuttings were removed from propagation trays and substrate was gently rinsed off the roots 14 d after cuttings were placed under supplemental light treatments. Stem caliper above the lowest leaf and stem length from the base of the cutting to the apical meristem were measured with a digital caliper (digiMax; Wiha, Schonach, Germany). Roots and leaves were excised from the stem and dried separately in an oven at 70 °C for 3 d.

After 3 d roots, stems, and leaves were weighed to determine root (RDM), stem (SDM), and leaf dry mass (LDM), respectively. Data calculated for each cutting included total dry mass (TDM; TDM = RDM + SDM + LDM), root:shoot dry-mass ratio [R:S; R:S = RDM/(SDM + LDM)], leaf mass ratio (LMR; LMR = LDM/TDM), stem mass ratio (SMR; SMR = SDM/TDM), root mass ratio (RMR; RMR = RDM/TDM), leaf area ratio (LAR; LAR = LA/TDM), specific leaf area (SLA; SLA = LA/LDM), and leaf mass area (LMA; LMA = LDM/LA).

Transplanted cuttings were monitored daily after planting. When the first flower opened, the date, flower bud number, node number beneath the first flower, and plant height from the surface of the substrate to the top of the plant were recorded. Time to flower was calculated as the time from the beginning of propagation to the first flower opening.

Experimental design and statistical analyses. The experiment used a randomized complete block design. The experiment was replicated three times over time. There were 10 samples (individual cuttings) per species per DLI per replication for morphological data and flowering plants, and five samples for gas-exchange measurements. Cuttings were randomly assigned to each DLI treatment, and DLI treatments were randomized between propagation dates within the greenhouse. Data were analyzed using regression analysis (SPSS 17.0; SPSS, Inc., Chicago, IL) with DLI as the independent variable.

Results

Impatiens. Growth and morphology of *Impatiens* were generally unaffected by supplemental light source (Table 4). Stem length and stem caliper ranged from 3.5 to 4.1 cm and 3.7 to 4.8 mm across replications, whereas the number of nodes ranged from 2.5 to 2.8 across replications. Similarly, LDM, SDM, and RDM were unaffected by supplemental light source and ranged from 100.2 to 165.4 mg, 23.6 to 41.0 mg, and 36.4 to 64.8 mg across replications, respectively. The LMR, SMR, RMR, and R:S ratio were 0.58 to 0.62, 0.13 to 0.15, 0.23 to 0.29, and 0.30 to 0.42, respectively, across replication and were unaffected by supplemental light source. The LA, LAR, and SLA were 23.3 to 59.1 cm^2, 0.112 $cm^2 \cdot mg^{-1}$, and 0.339 to 0.426 $cm^2 \cdot mg^{-1}$, respectively, across replications and were unaffected by supplemental light source.

Supplemental light source had no effect on F_v/F_m, P_n, g_S, and E and values measured ranged from 0.821 to 0.820, 3.3 to 5.9 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 0.274 $mol \cdot m^{-2} \cdot s^{-1}$, and 2.6 to 3.3 $\mu mol \cdot m^{-2} \cdot s^{-1}$, respectively, across replications. Similarly, R_d and ∞ were 0.636 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and 0.051, respectively, and were unaffected by supplemental light source. The P_{gmax} was 9.3 to 11.9 $\mu mol \cdot m^{-2} \cdot s^{-1}$ in the first and second replication and 5.7 $\mu mol \cdot m^{-2} \cdot s^{-1}$ in the final replication and was unaffected by supplemental light source. Similarly, the LCP and LSP were 7.3 to 12.0 $\mu mol \cdot m^{-2} \cdot s^{-1}$ or 497.3 to 618.3 $\mu mol \cdot m^{-2} \cdot s^{-1}$ across replications.

Impatiens flowered 58 d after the beginning of propagation for the first two replications and 72 d for the third replication. Similarly, the number of nodes below the flower, flower buds, and stem length were 2.6 to 4.6 nodes, 15 to 20 buds, and 6.0 to 9.3 cm, respectively, across replications and were unaffected by supplemental light source, whereas branch number and shoot dry mass were 4.0 to 4.9 branches and 2.63 to 5.4 g, respectively, across replications.

Pelargonium. Stem length and caliper were affected by replication, not supplemental lighting, and ranged from 3.8 to 5.3 cm and 6.4 to 7.0 mm, respectively, across replications, whereas node number was 5.5 nodes across supplemental light source and replication. RDM, SDM, and LDM were not affected by supplemental light source and ranged from 48.6 to 72.3 mg, 155.1 to 194.6 mg, and 443.8 to 612.7 mg, respectively, across replications. The LMR and SMR were 0.68 and 0.23, respectively, and were unaffected by supplemental light source and replication. The RMR and R:S ratio were 0.05 to 0.11 and 0.06 to 0.12, respectively, across replications but were unaffected by supplemental light source. Similarly, LA, LAR, and SLA were 83.3 to 101.1 cm^2, 0.057 $cm^2 \cdot mg^{-1}$, and 0.170 to 0.183 $cm^2 \cdot mg^{-1}$, respectively, across replications.

Chlorophyll fluorescence, P_n, g_S, and E were 0.825 to 0.834, 3.1 to 4.7 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 0.177 to 0.291 $mol \cdot m^{-2} \cdot s^{-1}$, and 2.3 $\mu mol \cdot m^{-2} \cdot s^{-1}$, respectively. Dark respiration was unaffected by supplemental light source and ranged from 0.70 to 1.57 $\mu mol \cdot m^{-2} \cdot s^{-1}$ across replications, whereas ∞ was unaffected by supplemental light source and replication and was 0.054. The LCP, LSP, and P_{gmax} were 10.9 to 22.4 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 404.2 to 621.2 $\mu mol \cdot m^{-2} \cdot s^{-1}$, and 10.0 to 13.53 $\mu mol \cdot m^{-2} \cdot s^{-1}$, respectively, across replications and were unaffected by supplemental light source.

Time to flower, branch number, and SDM were unaffected by supplemental light source or replication and were 48.7 d, 0.7 branches, and 5.2 g, respectively. Alternatively, nodes below the flower, flower bud number, and stem length were 5.8 to 7.5 nodes, 20.4 to 26.3 buds, and 6.4 to 8.0 cm, respectively, across replications and were unaffected by supplemental light source.

Petunia. Although stem length of *Petunia* was 5.2 to 6.3 cm across replications, supplemental light source also affected stem length (Fig. 2). For example, *Petunia* cuttings propagated under 100:0 red:blue LEDs were 0.5 to 0.6 cm shorter than cuttings propagated under HPS or 70:30 red:blue LEDs. Alternatively, stem caliper and the number of nodes were 2.5 mm and 7.4 nodes across replications regardless of supplemental light source. Although *Petunia* stem mass was 30.4 mg regardless of supplemental light source or replication, LDM and RDM were 87.7 to 105.3 mg and 24.4 to 34.9 mg, respectively, across replications. Additionally, LDM and RDM were influenced by supplemental light source (Fig. 2). For example, LDM and RDM of *Petunia* cuttings propagated under 70:30 red:blue LEDs were 14.0 mg and 8.6 mg greater than cuttings propagated under HPS lights. Although LMR, RMR, SMR, and R:S ratio were 0.57 to 0.66, 0.15 to 0.23, 0.19, and

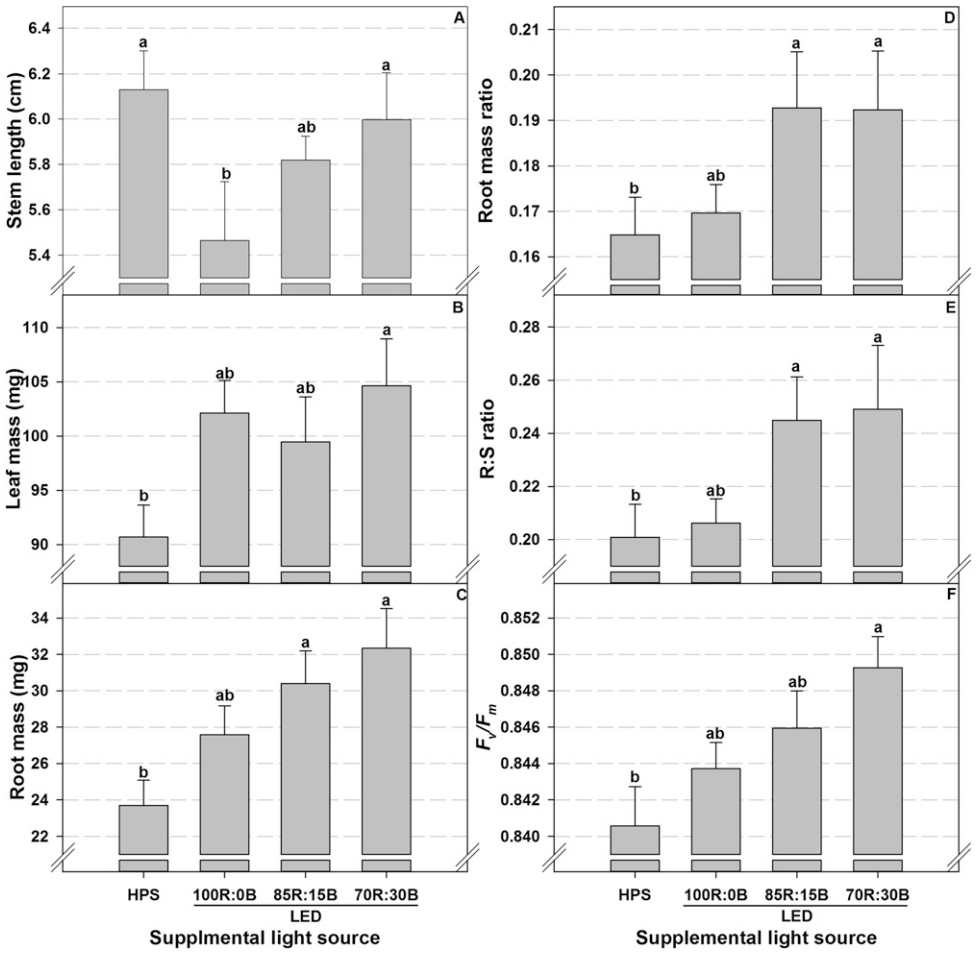

Fig. 2. (**A–I**) Effect of 70 μmol·m^{-2}·s^{-1} delivered from high-pressure sodium (HPS) lamps or light-emitting diodes (LEDs) with varying proportions of red:blue light during propagation on stem length, leaf mass, root mass, root mass ratio, root:shoot ratio, and chlorophyll fluorescence of *Petunia*. Different lower-case letters are significantly different by Tukey's honestly significant difference (HSD) test at $P \leq 0.05$.

0.19 to 0.31 across replications, respectively, supplemental light source only affected the RMR and R:S ratio (Table 3). For example, the RMR and R:S ratio were 0.03 and 0.05 greater, respectively, compared with cuttings grown under HPS lights. Leaf area, LAR, and SLA were unaffected by supplemental light source and replication and were 45.8 cm^2, 0.155 cm^2·mg^{-1}, and 0.524 cm^2·mg^{-1}, respectively.

The F_v/F_m of *Petunia* was affected by both replication and supplemental light source (Table 5) with F_v/F_m ranging from 0.837 to 0.849 across replications and 0.841 to 0.849 across supplemental light source (Fig. 2). The P_n, g_S, and E were 3.4 to 6.0 μmol·m^{-2}·s^{-1}, 0.288 mol·m^{-2}·s^{-1}, and 2.7 to 3.9 μmol·m^{-2}·s^{-1}, respectively, across replications and were unaffected by supplemental light source, whereas R_d and ∞ were 1.031 μmol·m^{-2}·s^{-1} and 0.058 regardless of supplemental light source or replication. The LSP and P_{gmax} were 822.0 μmol·m^{-2}·s^{-1} and 19.9 μmol·m^{-2}·s^{-1}, respectively, and were unaffected by supplemental light source or replication. Alternatively, although the LCP was 14.3 to 20.6 μmol·m^{-2}·s^{-1} across replications, it ranged from 14.4 μmol·m^{-2}·s^{-1} (100:0 red:blue) to 20.3 μmol·m^{-2}·s^{-1} (85:15 red:blue); there were no significant differences according to Tukey's honestly significant difference (data not shown).

Table 5. Analyses of variance for the effect of supplemental light source (S) and replication (R) on light response curves, and chlorophyll fluorescence.

	Impatiens		*Pelargonium*		*Petunia*	
Data	S	R	S	R	S	R
Chlorophyll fluorescence	NS[z]	***	NS	*	***	***
Photosynthesis	NS	***	NS	***	NS	***
Stomatal condutance	NS	NS	NS	**	NS	NS
Transpiration	NS	**	NS	NS	NS	***
Dark respiration	NS	NS	NS	***	NS	NS
Quantum use efficiency	NS	NS	NS	NS	NS	NS
Maximum photosynthesis	NS	***	NS	***	NS	NS
Light compensation point	NS	**	NS	***	*	**
Light saturation point	NS	*	NS	***	NS	NS

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

Although stem length and shoot dry mass were 15.9 to 19.3 cm and 2.0 to 2.5 g, respectively, across replications, supplemental light source also influenced both parameters (Table 6). For example, SDM and stem length of *Petunia* cuttings propagated under 85:15 red:blue LEDs were 0.3 g (10%) and 1.6 cm (15%) greater, respectively, compared with cuttings propagated under HPS lamps (Fig. 3). Time to flower, nodes below the flower, flower bud number, and branch number were 38 to 41 d, 8.6 to 10.1 nodes, 8.2 to 10.0 flowers, and 7.7 branches, respectively, across replications and were unaffected by supplemental light source.

Discussion

Although supplemental light source had no effect on the node number or stem caliper of any species, stem length of *Petunia* was shortest for cuttings propagated under 100:0 red:blue LEDs. *Impatiens* and, to a lesser extent, *Pelargonium* are shade-tolerant species, whereas *Petunia* is a shade-intolerant species (Armitage, 2001). The magnitude of stem elongation in response to red:far-red ratio is greater for shade-intolerant species such as *Petunia*.

There were few statistical or practical differences in growth, morphology, or gas

Table 6. Analyses of variance for the effect of supplemental light source (S), replication (R), and their interaction on flowering plant characteristics.

	Impatiens		*Pelargonium*		*Petunia*	
Data	S	R	S	R	S	R
Time to flower	NS[z]	***	NS	NS	NS	***
Nodes below the flower	NS	***	NS	***	NS	***
Stem length	NS	***	NS	*	*	***
Flower bud number	NS	*	NS	***	NS	***
Branches	NS	***	NS	NS	NS	**
Shoot dry mass	NS	***	NS	NS	*	**

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

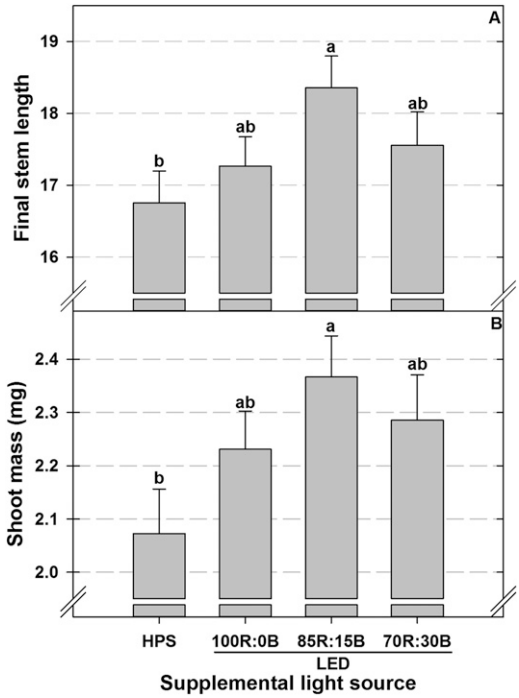

Fig. 3. Effect of 70 μmol·m^{-2}·s^{-1} delivered from high-pressure sodium (HPS) lamps or light-emitting diodes (LEDs) with varying proportions of red:blue light during propagation on final stem length and shoot mass at flowering of *Petunia*. Different lower-case letters are significantly different by Tukey's honestly significant difference (HSD) test at $P \leq 0.05$.

exchange for rooted cuttings across supplemental light sources within each species. We believe the primary reasons for this may be attributed to variation in biomass allocation during vegetative cutting propagation and node appearance rate during propagation. Currey and Lopez (2012) reported that during root development, LMR of *Impatiens hawkeri* 'Magnum Salmon' increased until root emergence, whereupon LMR decreased and RMR increased. Additionally, during the 3-week period cuttings were in propagation, approximately one, two, and five nodes appeared for *Impatiens*, *Pelargonium*, and *Petunia*, respectively. Therefore, although specific wavelengths including red and blue have been shown to impact morphology, reduced biomass allocation into leaves and stems taken together with a slow node appearance rate during root development likely diminished any photomorphogenic effects of specific wavelengths on shoot morphology.

The cause of enhanced biomass accumulation of *Petunia* cuttings grown under LEDs containing blue light compared with cuttings grown under HPS lamps is unclear. Although blue light has been reported to enhance stomatal opening (Assmann, 1993), we observed no differences in conductance or transpiration in cuttings across supplemental light source. However, the increased RMR and root:shoot ratio of petunia cuttings propagated with blue light from LEDs is likely the result of enhanced photosynthate availability and preferential allocation into roots over stem and leaf growth. Currey and Lopez (2012) reported that under higher DLIs, *Impatiens hawkeri* 'Magnum Salmon' allocated more carbon to root growth preferentially over stems and leaves.

We observed no significant differences in survey gas exchange or light response curves across light sources within species in our study. Similarly, survey measurements of P_n, and g_S of *Euphorbia pulcherrima* Wild. ex Klotsch 'Novia' did not vary across ambient light supplemented with 100 μmol·m^{-2}·s^{-1} supplied from HPS or 100 white or 87.5:12.5 red:blue LEDs (Bergstrand and Schüssler, 2012). Similarly, Hernández and Kubota (2012) reported no differences in P_n of *Lycopersicon esculentum* 'Komeett' at 1000 μmol·m^{-2}·s^{-1} for seedlings propagated under ambient light supplemented with 55.5 μmol·m^{-2}·s^{-1} provided from LEDs with red:blue ratios of 100:0, 96:4, or 84:16. Relative quantum efficiency has two broad peaks in the red and blue ranges (McCree, 1972). The similar yield photon flux of the supplemental light sources, taken with the lack of significant differences in gas exchange for plants grown with solar light supplemented with LED light varying in spectral composition, may suggest that spectral responses may be saturated at higher light levels.

We observed little effect of supplemental light source on growth and morphology of finished plants, including time to flower, stem length, node number below the first flower or inflorescence, flower bud number, and SDM. The only significant effects observed were greater stem length and dry mass of *Petunia* propagated under 85:15 red:blue light compared with HPS lamps. However, although these differences are statistically significant, they are commercially insignificant. The lack of significant differences among supplemental light source during propagation on flowering plants within a species further supports the conclusion that although some characteristics of rooted *Petunia* cuttings were affected by supplemental light source, these effects appeared to be transient in nature.

Although analyses of variance indicated supplemental light source had little impact on plant characteristics, replication was frequently a significant effect. For example, *Impatiens* cuttings received in the third replication were smaller than the previous two replications. The impact of smaller cuttings was observed in the lower RDM after 14 d and an increase in nodes below the first flower for flowering plants compared with the first two replications. However, when the variation across replication is considered, although there were statistically significant differences between replications within a species, these differences were not considered commercially significant. We attribute much of the variation within species across replications to variation in propagules. Although off-shore cutting producers strive to maintain uniformity in the cuttings exported to propagators, variation in stem-tip cuttings can occur over time as a result of several factors, including number of stock plants in production and demand for cuttings. Additionally, although stock plant facilities often create species- and cultivar-specific guidelines for target cuttings specifications, including stem length, node or leaf number, and leaf size, there are upper and lower limits to these parameters, which contribute to commercially acceptable variation among and within batches of cuttings harvested and shipped.

Although not a central focus of this study, the energy consumption and efficiency of supplemental light sources warrant some discussion. The daily energy consumption of

the HPS and 100:0, 85:15, or 70:30 red:blue LEDs was 3.01, 3.29, 3.43, and 4.06 kWh·d^{-1}, respectively. Although the LEDs consumed more energy, the fans used to cool the arrays consumed 1.49 kWh·d^{-1} and accounted for 37% to 45% of the total energy consumption for each LED array. Therefore, if passively cooled through the use of a heat sink as opposed to actively cooled using fans, the energy consumption for the 100:0, 85:15, or 70:30 red:blue LEDs would be 1.80, 1.93, and 2.57 kWh·d^{-1}, respectively, and result in a 15% to 40% reduction in energy use compared with HPS lights. Although the use of a passive heat sink would reduce the energy use and, thus, operating costs of the LED lights, a passive heat sink would likely increase the size of the fixtures and initial investment cost (M. Bourget and B. Morrow, personal communication). The majority (≈90%) of heat generated by LEDs is dissipated through conduction as opposed to convection like HPS lamps; therefore, the materials used in constructing LED arrays play a major role in thermal dissipation (Arik et al., 2004; Christensen and Graham, 2009). Because the low total *PPF* required for LEDs used for photoperiodic lighting such as day extension or night interruption is small (1 to 2 μmol·m^{-2}·s^{-1}), passively cooled or minimally actively cooled LED lights will likely be used (Craig and Runkle, 2012). However, the total *PPF* required for photosynthetic lighting is much greater and poses a challenge with regard to constructing energy-efficient, high-intensity LED systems with minimal shading for use in overhead lighting.

Conclusions

When our data on the effect of supplemental light source during propagation on growth, morphology, and gas exchange of cuttings at the end of propagation are taken together with data collected for flowering plants finished in a common environment, there is no significant difference between HPS lamps and LEDs. Furthermore, we observed no significant differences among LEDs varying in their spectral composition of red and blue light. Therefore, the paucity of both statistically and commercially significant differences or negative effects of LEDs on growth and development during subsequent forcing after transplant further supports the transient nature of the impact of supplemental light quality during propagation of cuttings.

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