Comparison of Supplemental Lighting from High-pressure Sodium Lamps and Light-emitting Diodes during Bedding Plant Seedling Production

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Abstract. Annual bedding plant seedlings or plugs are considered high quality when they are compact, fully rooted transplants with a large stem caliber and high root dry mass. Greenhouses in northern latitudes rely on supplemental lighting (SL) from high-pressure sodium lamps (HPS) during winter months to achieve high-quality, finished plugs. Light-emitting diodes (LEDs) offer higher energy efficiencies, a long operating life, and precise waveband specificity that can eliminate wavebands not considered useful. Seedlings of Antirrhinum, Catharanthus, Celosia, Impatiens, Pelargonium, Petunia, Tagetes, Salvia, and Viola were grown at 21 °C under a 16-hour photoperiod of ambient solar light and SL of 100 μmol·m−2·s−1 from either HPS lamps or LED arrays with varying proportions (%) of red:blue light (100:0, 85:15, or 70:30). Height of Catharanthus, Celosia, Impatiens, Petunia, Tagetes, Salvia, and Viola was 31%, 29%, 31%, 55%, 20%, 9%, and 35% shorter, respectively, for seedlings grown under the 85:15 red:blue LEDs compared with those grown under HPS lamps. Additionally, stem caliber of Antirrhinum, Pelargonium, and Tagetes was 16%, 8%, and 13% larger, respectively, for seedlings grown under the 85:15 red:blue LEDs compared with seedlings grown under HPS lamps. The quality index (Q), a quantitative measurement of quality, was similar for Antirrhinum, Catharanthus, Impatiens, Pelargonium, and Tagetes grown under LEDs and HPS lamps. However, it was significantly higher for Petunia, Salvia, and Viola under 85:15, 70:30, and 100:0 red:blue LEDs than under HPS lamps, respectively. These results indicate that seedling quality for the majority of the species tested under SL from LEDs providing both red and blue light was similar or higher than those grown under HPS lamps.

Annual bedding plant sales for the 15 top-producing states were over $1.4 billion in 2012, the highest of any sector of the U.S. commercial floriculture industry (U.S. Dept. of Agriculture, 2013). Advancements in production of bedding plant seedlings, also known as young plants or plugs, have led to a large increase in finish plant quality and profitability (Armitage and Kacperski, 1994; Kuehny et al., 2001). Young plant production occurs in late winter and early spring when temperatures as high as 450 °C and requires separation of lamps from plants to prevent leaf scorch (Fisher and Both, 2004; Nelson, 2012; Sherrard, 2003; Spaargaren, 2001). LEDs are solid-state, semiconducting diodes that can emit narrow spectra of light from 400 nm to 1000 nm or greater and have been considered for use as sole source and SL (Barta et al., 1992; Bourget, 2008; Bula et al., 1991; Massa et al., 2008). The peak wavelengths of greatest interest for studies of plant growth and development include blue (450 nm), red (660 nm), and far-red (730 nm). Recently, LEDs have achieved an efficiency of 38% (red) to 50% (blue) converting electrical energy to photons (Philips Lumileds, 2011) and have an estimated lifespan of 50,000 h or greater (Bourget, 2008). Light-emitting diodes offer the ability to test wavelength combinations to manipulate plant morphology and control plant stature (Folta and Childers, 2008; Stutte, 2009). Light quality has been shown to have a significant effect on plant growth, development, and physiology (Brown et al., 1995; Sage, 1992; Smith, 1982). Previous studies have focused on the use of LEDs as sole-source lighting in highly controlled and enclosed environments (Massa et al., 2008), as a SL source for intercanopy (Dueck et al., 2006; Hou-Pekkanen et al., 2006; Trouwborst et al., 2010), or overhead (Dueck et al., 2012) lighting for greenhouse vegetable production, or propagation of ornamental cuttings (Currey and Lopez, 2013). Using LEDs requires determining the best light quality for each crop (Massa et al., 2008).

For example, when Zantedeschia jucunda K. Koch ‘Black Magic’ (calla lily) was grown in vitro under a total PPF of 80 μmol·m−2·s−1 of varying proportions of red and blue light from LEDs, stem elongation, but not dry mass, could be manipulated. As blue light increased from 0 to 32 μmol·m−2·s−1 and red light was reduced from 80 to 48 μmol·m−2·s−1 (red/blue ratio = 1.5), stem elongation decreased from 10.5 to 8.5 cm (Jao et al., 2005). In a separate study, van Ieperen et al. (2012) grew Cucumis sativus L. (Hoffman Gianta’ cucumber) in growth chambers under LEDs providing a PPF of 100 μmol·m−2·s−1 of 100:0, 100:0, or 70:30 red:blue light over a 16-h photoperiod. Petiole length of plants grown under 70:30 red:blue LEDs was reduced by 1.0 cm, whereas stomatal density and net leaf photosynthesis increased by 248 mm−2 and 1.2 μmol CO2 per m−2·s−1, respectively, compared with plants grown under monochromatic red light. Hernández and Kubota (2012) demonstrated the benefits of greenhouse SL on the growth and development of Solanum lycopersicum L. ‘Komeeti’ (tomato) seedlings grown under solar DLI’s of 8.9 to 19.4 μmol·m−2·s−1 and LED SL providing a PPF of 56 μmol·m−2·s−1. However, there were no significant differences in shoot dry mass, leaf count, stem diameter, hypocotyl length, leaf area, or chlorophyll concentration among the different LED SL treatments providing red/blue PPF ratios of 100:0, 96:4, or 84:16. Another study demonstrated no...
differences in productivity for greenhouse-grown tomato 'Komeett' and 'Success' grown under overhead HPS lamps or intracanopy LEDs towers providing 95:5 red:blue light (Gómez et al., 2013).

To our knowledge, no previous studies have quantified the effects of narrow-spectra high-intensity LEDs as a SL source for annual bedding plant seedlings. The objectives of this study were to: 1) quantify the effects of SL from three LED sources of different light quality and HPS lamps on seedling growth, morphology, and quality; and 2) determine whether there were any residual effects of SL source on subsequent growth and development after transplant in a common environment.

Materials and Methods


Supplemental lighting treatments. Seedlings were grown under ambient solar light supplemented with 100 μmol·m⁻²·s⁻¹ PPF at plant height [as measured with a spectroradiometer (PS-100; Apogee Instruments, Logan, UT)] from 0600 to 2200 μs, which provided a supplemental DLI of 5.8 mol·m⁻²·d⁻¹. Supplemental light was delivered from a 150-W HPS lamp (PL2000; P.L. Lights, Beavissville, Ontario, Canada) or one of three LED arrays (Philips GreenPower LED research module; Koninklijke Philips Electronics N.V., The Netherlands). Each group of LED arrays was spaced on 6.3-cm centers and consisted of 48.5-cm-long and 3.3-cm-wide square aluminum bars containing five 660- or 470-nm LEDs. The 100:0, 85:15, and 70:30 red:blue ratio treatments contained 20 red bars, 18 red and four blue bars, and 15 red and seven blue bars alternating, respectively. Spectral scans of SL were taken at night at the beginning and end of each replication with a spectroradiometer (PS-100; Apogee Instruments, Inc.). Spectral quality of SL sources is shown in Figure 1. Electrical use (kWh·d⁻¹) for both HPS lamps and LED lights was measured using an electrical meter (P440 Kill A Watt; P3 International, New York, NY).

Table 1. Average plant temperatures and daily light integral (DLI) under ambient solar daylight supplemented with ≈100 μmol·m⁻²·s⁻¹ delivered from high-pressure sodium (HPS) lamps or light-emitting diodes with varying proportions of red (R) and blue (B) light from 0600 to 2000 μs.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Supplemental light source</th>
<th>Supplemental light (μmol·m⁻²·s⁻¹)</th>
<th>Solar DLI (mol·m⁻²·d⁻¹)</th>
<th>Plant temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29 Mar.</td>
<td>HPS</td>
<td>102.4 ± 6.8</td>
<td>7.1 ± 2.1</td>
<td>19.5 ± 2.6</td>
</tr>
<tr>
<td></td>
<td>100R:0B</td>
<td>98.4 ± 1.2</td>
<td>8.4 ± 3.3</td>
<td>18.2 ± 3.1</td>
</tr>
<tr>
<td></td>
<td>85R:15B</td>
<td>99.9 ± 2.2</td>
<td>7.7 ± 1.5</td>
<td>18.4 ± 3.2</td>
</tr>
<tr>
<td></td>
<td>70R:30B</td>
<td>99.2 ± 3.1</td>
<td>5.2 ± 1.2</td>
<td>17.7 ± 2.5</td>
</tr>
<tr>
<td>24 May</td>
<td>HPS</td>
<td>97.6 ± 3.2</td>
<td>6.8 ± 2.0</td>
<td>22.2 ± 3.5</td>
</tr>
<tr>
<td></td>
<td>100R:0B</td>
<td>101.5 ± 3.6</td>
<td>5.1 ± 1.5</td>
<td>21.0 ± 2.7</td>
</tr>
<tr>
<td></td>
<td>85R:15B</td>
<td>98.7 ± 3.6</td>
<td>5.6 ± 1.5</td>
<td>21.0 ± 4.0</td>
</tr>
<tr>
<td></td>
<td>70R:30B</td>
<td>98.4 ± 5.7</td>
<td>5.6 ± 1.6</td>
<td>20.7 ± 3.1</td>
</tr>
<tr>
<td>18 Sept</td>
<td>HPS</td>
<td>97.8 ± 3.6</td>
<td>2.6 ± 1.1</td>
<td>19.8 ± 2.8</td>
</tr>
<tr>
<td></td>
<td>100R:0B</td>
<td>97.2 ± 2.1</td>
<td>3.4 ± 1.8</td>
<td>18.3 ± 1.9</td>
</tr>
<tr>
<td></td>
<td>85R:15B</td>
<td>99.2 ± 2.9</td>
<td>2.8 ± 1.2</td>
<td>18.0 ± 2.1</td>
</tr>
<tr>
<td></td>
<td>70R:30B</td>
<td>93.8 ± 2.4</td>
<td>3.0 ± 1.7</td>
<td>18.4 ± 2.4</td>
</tr>
<tr>
<td>23 Oct.</td>
<td>HPS</td>
<td>93.1 ± 3.3</td>
<td>2.7 ± 1.9</td>
<td>20.7 ± 2.4</td>
</tr>
<tr>
<td></td>
<td>100R:0B</td>
<td>98.6 ± 3.9</td>
<td>2.4 ± 1.5</td>
<td>18.6 ± 1.9</td>
</tr>
<tr>
<td></td>
<td>85R:15B</td>
<td>101.4 ± 1.8</td>
<td>2.4 ± 1.8</td>
<td>19.0 ± 2.1</td>
</tr>
<tr>
<td></td>
<td>70R:30B</td>
<td>97.6 ± 2.7</td>
<td>2.1 ± 1.0</td>
<td>18.4 ± 2.4</td>
</tr>
</tbody>
</table>

*Celosia, Petunia, Impatiens, Tagetes, and Viola were placed under treatments on 29 Mar. and 24 May and Antirrhinum, Catharanthus, Pelargonium, and Salvia were placed under treatments on 18 Sept. and 23 Oct.

Data collection and calculations. At 14, 21, and 28 d after initiating SL treatments, 25 plants of each species were randomly harvested and measured for pullability (the number of seedlings that can be pulled from the tray with roots and media intact). The collective roots and shoots of the 25 plants were washed and placed in a drying oven at 70 °C. After 4 d, roots and shoots were weighed to determine collective root dry mass (RDM) and shoot dry mass (SDM), respectively.

At 28 d after initiating SL treatments, 10 plants from each species were randomly selected and measured for stem length (measured from the base of the hypocotyl to the shoot apical meristem) and stem caliper above the lowest leaf with a digital caliper (digiMax; Wiha, Schonach, Germany). Relative chlorophyll content was measured with a SPAD meter (SPAD-502; Konica Minolta Sensing, Inc., Osaka, Japan). After nondestructive measurements were recorded, roots and shoots of all selected seedlings were washed and separated, placed in a drying oven at 70 °C for at least 4 d, and RDM and SDM were recorded. The sturdiness quotient (SQ) was calculated as stem caliper divided by stem length. The QI, an objective, integrated, and quantitative measurement of quality, was calculated as the [total dry mass (shoot+root) ratio + sturdiness quotient] (Currey et al., 2013).

Transplants in the finish environment were monitored daily after planting. When
the first flower opened, the date, node number 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 flower opening.

Statistical analysis. The experiment used a complete block design replicated twice in time for each of the nine species. There were 10 samples (individual plants) per species per SL treatment for seedling and finish data. Data were analyzed using SAS (SAS 9.3; SAS Institute Inc., Cary, NC) mixed model procedure (PROC MIXED) for analysis of variance.

Results

Height. Height of all species with the exception of Pelargonium was significantly shorter under LED SL treatments (Fig. 2A–C). For example, height of Catharanthus, Celosia, Impatiens, Petunia, Salvia, Tagetes, and Viola was 31%, 29%, 31%, 55%, 20%, 9%, and 35% shorter for seedlings grown under the 85:15 red:blue LEDs compared with those grown under HPS lamps, respectively. Antirrhinum seedlings under 70:30 red:blue LEDs were 9% shorter than those grown under HPS lamps.

Stem caliper. Stem caliper of Antirrhinum, Pelargonium, and Tagetes seedlings was significantly larger under LED treatments (Fig. 2D–F). For example, stem caliper of Antirrhinum, Pelargonium, and Tagetes was 16%, 8%, and 13% larger, respectively, for seedlings grown under the 85:15 red:blue LEDs compared with seedlings grown under HPS lamps. Under 70:30 red:blue LEDs, stem caliper of Celosia and Viola seedlings was significantly smaller than under the other SL treatments. Stem caliper of Celosia grown under 70:30 red:blue LEDs was 9% smaller than plants grown under HPS lamps. Stem caliper of Catharanthus, Impatiens, Petunia, and Salvia was not significantly influenced by SL treatments.

Root dry mass. Root dry mass of Celosia and Impatiens was highest under the HPS lamps and 100:0 red:blue LEDs (Fig. 2G–I). However, RDM of Petunia, Salvia, and Viola was lowest under the 70:30 red:blue LEDs. For example, RDM of Salvia was 36% lower for plants grown under 70:30 red:blue LEDs than under HPS lamps. There were no significant differences in RDM between HPS and LED SL treatments for Antirrhinum, Catharanthus, Pelargonium, and Tagetes.

Shoot dry mass. Shoot dry mass of Celosia was highest under the HPS and 100:0 red:blue LEDs (Fig. 2J–L). The SDM of Impatiens, Petunia, Salvia, and Viola was lowest under the 70:30 red:blue LEDs. For example, SDM of Impatiens, Petunia, Salvia, and Viola was 18%, 25%, 24%, and 40% lower under 70:30 red:blue LEDs, respectively, than under HPS lamps. However, there were no significant differences in SDM of Antirrhinum, Catharanthus, Pelargonium, and Tagetes between HPS and LED SL treatments.

Sturdiness quotient. Sturdiness quotient of Antirrhinum, Catharanthus, Impatiens, Pelargonium, Petunia, Tagetes, and Viola was highest under LED SL treatments (Fig. 3A–C). For example, SQ of Antirrhinum and Pelargonium was 22% and 23% higher under the 70:30 red:blue LEDs when compared with HPS lamps. Sturdiness quotient of Impatiens was 54% higher under 85:15 red:blue LEDs than plants grown under HPS lamps. For Celosia and Salvia, SQ was not significantly different between HPS and LED SL treatments.

Root:shoot ratio. Root:shoot ratio was highest under LED SL treatments for Catharanthus, Impatiens, Petunia, Salvia, and Viola (Fig. 3D–F). For example, root:shoot ratio of Catharanthus and Impatiens was 27% and 23% higher under the 70:30 red:blue LEDs and 100:0 red:blue LEDs, respectively, than under HPS lamps. However, root:shoot ratio was lowest under the 70:30 red:blue LEDs for Celosia and Tagetes. No significant differences between HPS and LED SL treatments were found for root:shoot ratio of Antirrhinum and Pelargonium.

Quality index. Under LED SL treatments, QI of Petunia, Salvia, and Viola was highest compared with HPS lamps (Fig. 3G–I). For example, QI of Petunia, Salvia, and Viola was 68%, 30%, and 33% higher under 85:15, 70:30, and 100:0 red:blue LEDs, respectively, than under HPS lamps. Quality index of Pelargonium was highest under the HPS lamps. Quality index was not significantly influenced by SL treatment for Antirrhinum, Catharanthus, Impatiens, Pelargonium, and Tagetes.

Relative chlorophyll content. Relative chlorophyll content was highest under LED SL treatments for Antirrhinum, Catharanthus, Impatiens, Pelargonium, and Salvia (Fig. 3J–L). For example, relative chlorophyll content was 21% and 15% higher, respectively, for Pelargonium and Salvia seedlings grown under 70:30 red:blue LEDs than under HPS lamps. However, relative chlorophyll content of Catharanthus was not significantly different under HPS or LED SL treatments.

Height at flower. Catharanthus and Pelargonium were shorter at flower when grown under HPS lamps compared with LED SL treatments (Fig. 4A–C). For example, Pelargonium was 42% shorter at the time of flower when grown under HPS lamps compared with 100:0 red:blue LEDs. However, height at the time of first open flower was not significantly different for Antirrhinum, Celosia, Impatiens, Petunia, Salvia, Tagetes, or Viola grown under HPS or LED SL treatments.

Nodes below open flower. Celosia had more nodes below the first open flower when grown under 70:30 red:blue LEDs compared with other SL treatments; however, Impatiens and Petunia had fewer nodes below the first open flower when grown under 70:30 red:blue LEDs compared with other SL treatments (Fig. 4D–F). Petunia, for example, had two fewer nodes below the first open flower for plants grown under 70:30 red:blue LEDs compared with HPS lamps. No significant difference in the number of nodes below the first open flower was observed for Antirrhinum, Catharanthus, Pelargonium, Salvia, Tagetes, and Viola grown under HPS or LED SL treatments.

Time to flower. TTF for Pelargonium occurred 20 d earlier for plants grown under 70:30 red:blue LEDs compared with plants grown under 100:0 red:blue LEDs (Fig. 4G–I). TTF of Celosia, Impatiens, Salvia, and Tagetes was generally slower for plants grown under LEDs compared with HPS lamps. However, TTF was not significantly different for plants grown under HPS or LED SL treatments for Antirrhinum, Catharanthus, Petunia, and Viola.

Discussion

A high-quality seedling is one that is compact, fully rooted with a large stem caliper and high RDM. Compact seedlings with a large stem caliper and RDM are less likely to be damaged during shipping and transplant (Pramuk and Runkle, 2005b). The QI is a useful tool to assess young plant quality by
integrating the morphological parameters that contribute to the perceived quality of plugs and liners (Currey et al., 2013). In our study, parameters of seedling quality using the QI were similar to HPS lamps or higher for Antirrhinum, Catharanthus, Impatiens, Petunia, Pelargonium, Salvia, Tagetes, and Viola grown under LED SL for 28 d. Celosia was the only species in which the QI was lowest under LED treatments providing blue light. Antirrhinum, Catharanthus, Impatiens, Pelargonium, Petunia, and Tagetes grown under the 85:15 and 70:30 red:blue LEDs were generally more compact with a larger stem caliper, higher SQ, and higher relative chlorophyll content than plants grown under HPS lamps. The RDM of these species was statistically similar to those produced under HPS lamps. However, SDM of Impatiens and Petunia was lower when seedlings were grown under LEDs containing blue light. Several studies have highlighted the importance of blue light when used as a sole source or SL. For example, the number of tillers in Triticum aestivum L. ‘USU-Super Dwarf’ (wheat) was similar under 90:10 red:blue LEDs as plants grown under white light. Additionally, 15 d after transplant, SDM increased from 0.85 to 1.42 g and photosynthesis increased from 5.3 to 8.3 μmol CO₂ per m²·s⁻¹ as the proportion of blue light supplementing red light increased from 1% to 10% (Goins et al., 1997). Dueck et al. (2012) demonstrated that leaf thickness of ‘Sunstream’ tomato plants increased by 12% when grown under LEDs with a ratio of 88:12 red:blue light compared with those grown under HPS lamps. When Arabidopsis thaliana L. plants were grown under 100:0 red:blue LEDs, they exhibited abnormal leaf morphology, delayed flowering, and reduced seed production. However, 90:10 red:blue fluorescent light resulted in plants that had a similar TTF and increased germination rate compared with plants grown under HPS lamps. When cuttings of Impatiens hawkeri W. Bull ‘Celebrette Frost’ and Pelargonium hortorum L.H. Bailey ‘Designer Bright Red’ were grown under SL from HPS lamps, 100:0, 85:15, or 70:30 red:blue LEDs, no significant differences in growth and morphology were observed. However, leaf dry mass, root dry mass, root mass ratio, and root:shoot ratio increased 15%, 36%, 17%, and 24%, respectively, for petunia ‘Suncatcher Midnight Blue’ cuttings grown under 70:30 red:blue LEDs compared with HPS lamps (Currey and Lopez, 2013).

Our results show that relative chlorophyll content increased as the amount of blue light increased for some species. XiaoYing et al. (2011) focused on the cellular changes that result from using different color wavelength LEDs on tomato. Plants grown under any LED treatment with blue light had significantly thicker leaves and longer palisade cells than plants grown in other LED treatments. For example, leaf thickness and palisade cell length were 23.1 and 2.5 μm under 100:0 red:blue LEDs, they increased to 35.9 and 14.4 μm under 50:50 red:blue LEDs, a 55.4 and 476.0% increase, respectively. Additionally, chloroplasts were more developed and stomata density increased under the red:blue LEDs compared with the monochromatic red LEDs. Additionally, enhanced net photosynthesis was measured for leaves irradiated with blue LEDs. Similarly, our study demonstrated that relative chlorophyll content increased by 21% and 15% for Pelargonium and Salvia grown under 70:30 red:blue LEDs compared with HPS lamps, respectively.
TTF of *Celosia*, *Impatiens*, *Salvia*, and *Tagetes* was reduced for plants grown under the HPS lamps compared with most of the LED treatments. We postulate that hastened flowering could be attributed to increased seedling temperature of \(25^\circ C\) under HPS lamps (Table 1). High-pressure sodium lamps are rated to be 25% to 30% efficient at converting electrical energy to light; the other 70% to 75% is radiated as heat energy (Spaargaren, 2001).

*Celosia* is the only species considered cold-sensitive and must be grown under higher temperatures because it has an estimated base temperature of 10 \( ^\circ C \) (Runkle and Blanchard, 2011). Pramuk and Runkle (2005a) demonstrated the influence of temperature and use of SL from HPS lamps on development of *Celosia*. TTF was quadratically related to DLI and temperature; as temperature increased up to \(25^\circ C\) and DLI increased from 5 to 15 mol·m\(^{-2}\)·d\(^{-1}\), TTF decreased. However, further increase in DLI had no significant effect on TTF. Additionally, as temperature increased from 15 to 28 \(^\circ C\) under an average DLI of 8 mol·m\(^{-2}\)·d\(^{-1}\), plant height increased from 17 to 27 cm (37%). When HPS lamps were used to increase the DLI from 5 to 25 mol·m\(^{-2}\)·d\(^{-1}\), shoot dry mass doubled from 3.6 to 7.2 g for plants grown under 25 \(^\circ C\).

Previous studies with bedding plants have demonstrated that increased DLI during the young plant stage results in earlier flowering during the finish stage (Hutchinson et al., 2012; Lopez and Runkle, 2008; Oh et al., 2010). For example, increasing DLI with SL later in the plug stage for petunia ‘Madness Red’ and pansy ‘Delta Premium Yellow’ resulted in earlier flowering but lower dry mass and bud number than in the first one- or two-thirds of production. Supplemental lighting during the entire plug stage and last two-thirds of the plug stage reduced TTF by 4.8 and 4.7 d in petunia and 4.7 and 5.7 d in pansy, respectively, when compared with the photoperiodic low light control (Oh et al., 2010). Similarly, as DLI increased from 1.2 to 12.3 mol·m\(^{-2}\)·d\(^{-1}\), TTF decreased by 23 and 19 d for *Angelonia angustifolia* ‘AngelMist White Cloud’ and *Osteospermum ecklonis* ‘Voltage Yellow’, respectively (Hutchinson et al., 2012). Although we did not have a treatment without supplemental lighting, we provided the same DLI with all our SL treatments and determined that TTF was similar for *Antirrhinum*, *Catharanthus*, *Petunia*, and *Viola* grown under the HPS lamps and LEDs.

Although energy consumption and efficiency of SL sources were not a primary focus of this study, they do warrant mentioning. The daily energy consumption for the HPS, 100:0, 85:15, and 70:30 red:blue was as follows: 3.01, 1.23, 1.35, and 1.56 kWh·d\(^{-1}\), respectively. Energy consumption from the LEDs to light five plug trays decreased by 59.1%, 55.1%, and 48.2% for the 100:0, 85:15, and 70:30 red:blue LED arrays, respectively, compared with one 150-W HPS lamp. The LED arrays used in this study were passively cooled and therefore did not use any additional energy for active cooling as compared with the LEDs used by Currey and Lopez (2013). As a result of using passively cooled LEDs, ambient solar radiation was blocked by 50% as a result of the increased size of the fixtures. Currey and Lopez (2013) found that using actively cooled LEDs with forced-air cooling consumed 3.29, 3.43, and 4.06 kWh·d\(^{-1}\) for 100:0, 85:15, and 70:30 red:blue LEDs, respectively, compared with HPS lamps that used 3.01 kWh·d\(^{-1}\). They calculated the energy consumption of the fans used to cool the arrays and reported that...
they accounted for 37% to 45% of the energy consumed by the LED arrays. Without fans, the LED arrays showed a 15% to 40% energy reduction compared with the HPS lamps. The need for heat dissipation without significant shading poses challenges to developing LED arrays for greenhouse use, because the materials used to construct LED arrays are important factors for thermal dissipation (Bourget, 2008; Christensen and Graham, 2009).

Conclusions

The QIs of the majority of species tested in this study were similar or higher for plants grown under SL from LEDs containing both red and blue light compared with those seedlings grown under HPS lamps. For species in which TTF was delayed when seedlings were grown under LEDs, the delay was not commercially significant with the exception of Celosia and Salvia. Therefore, a light ratio of 85:15 red/blue light could be a good combination for greenhouse LED SL of bedding plant plugs. However, it is also important to remember that although blue LEDs have a higher electrical conversion efficiency compared with red LEDs, blue light is a higher energy light, which increases energy consumption as higher proportions of blue are used. Therefore, further research is necessary to determine if lower amounts of blue light can yield adequate plant responses. Our results indicate that providing SL from LEDs or HPS lamps has a positive influence on seedling RDM, height, and stem caliper leading to high-quality bedding plant seedlings when solar light is limiting.

Literature Cited


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