LED or HPS in ornamentals?

A case study in roses and campanulas

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Summary

The aim of the experiment was to evaluate the effect of novel top-installed high-output light-emitting diodes (LEDs) on ornamental plant production both in terms of productivity and energy use in comparison with conventional HPS lamps in two standard greenhouse compartments. The experiments were performed in late winter period using three varieties of potted miniature roses (*Rosa hybrida*) and two cultivars of *Campanula* grown in identical installed supplemental light levels (75–85 $\mu\text{mol m}^{-2} \text{s}^{-1}$ of PPFD) with temperature set points 18°C at night, 24°C during the day, while 800 ppm of CO₂ was supplied. Due to the winter being relatively cold, the set points were equal to the realized temperature as ventilation rarely occurred. The leaf temperature was maintained at the same level by adjusting the top pipe temperature. Two harvests were performed in February and in March to show the potential effect of winter- or early spring- grown plants. The results showed relatively small differences with respect to plant performance between the HPS and LED treatments, and most significant differences were found only in the 1st batch of roses harvested in February regarding plant height and stem fresh and dry weight, indicating that growth was favored under HPS lamps for three out of four cultivars. Both the 2nd batches for roses and campanulas harvested in March showed very limited or no differences between treatments. The energy saving on the electricity side was 60% in LEDs compared to HPS, but due to the increased heat use from top pipes the energy used for heating increased by around 50% over the whole experimental period.

Keywords

energy saving, light sources, ornamentals, greenhouses

Introduction

The use of light emitting diodes (LEDs) has been extensively studied in greenhouse cultivation for many years now. A broad range of LED lamps and configurations for plant production has been under development. LED technologies are relatively energy-efficient, regarded as long lasting and flexible in use. The LEDs as such have proved relatively long-lived with lifespans of 25,000 hrs. However, the electronic components might be shorter, thus the life expectancy of the luminaries will be lower (Morrow, 2008). In addition, indi-

Significance of this study

What is already known on this subject?

- LED are more efficient in energy use and the opportunity to manipulate the spectral composition can be beneficial for plant growth and development.

What are the new findings?

- No substantial differences in appearance, morphology and development of LED- or HPS-grown plants, while flowering is not substantially affected by supplemental red and blue LED lighting compared to the HPS spectrum.

What is the expected impact on horticulture?

- LED-based supplemental lighting saved 60% energy used for electricity compared to HPS lamps, whereas energy used for heating increased by 50% in the greenhouse with LED lighting compared to the HPS.

vidual diodes cannot be replaced, while in traditional HPS lamps the bulb is replaced, when reaching a certain stage of exhaustion.

The LED lamps have been promoted to reduce the energy use, but also for various growth controlling aspects (Hogewoning et al., 2010; Yorio et al., 2001) and have been claimed to change the balance between primary and secondary metabolites (Darko et al., 2014). The use of LEDs in greenhouses provides an opportunity to control light spectrum and the focus is to use high-efficiency lamps that replace traditional HPS lamps as the effect of natural light in many cases might disturb or reset spectral effects outside the darkest period. However, up to date, the published results in terms of LED use are not conclusive for greenhouse use yet, as the heterogeneity of the lamps from different producers and spectral compositions, combined with a certain lack of standards for characterizing new lamps (watt per produced photon yield in an adequate area and distance from the lamp), makes comparisons very difficult (Nelson and Bugbee, 2004). Comparisons of different LED types show differences in growth linked to red:blue ratios (Li et al., 2016). For plant factories the use of LED lighting is an alternative to HPS, due to the reduced heat emission (Kim et al., 2004; van Ieperen and Trouwborst, 2008).

In Denmark and other Northern European countries, supplemental lighting is used to enhance plant growth from fall to spring. HPS lamps do not offer spectral manipulation. On the contrary, light spectrum can be manipulated with the

TABLE 1. Energy use for supplemental lighting and heating in the two greenhouse compartments where the light source were either light-emitting diodes (LEDs) or high-pressure sodium (HPS) lamps. Energy use was recorded on a daily basis by a climate computer (LCC, Completa, Sønderød, Denmark).

Month	Treatment	Electricity use (kWh m ⁻²)	Energy use for heating (kWh m ⁻²)			Total energy use (kWh m ⁻²)
			Top pipe	Bottom pipe	Total	
January	HPS	111	20.8	55.0	75.8	187
	LED	44.3	72.9	58.4	131	176
February	HPS	105	48.7	71.3	120	225
	LED	41.9	107	61.1	168	210
March	HPS	84.1	13.1	34.5	47.7	132
	LED	33.5	58.2	31.6	89.7	123
Total	HPS	300	83	161	243	544
	LED	119	238	151	389	509
Effect %		-60.4	+186.8	-6.2	+60.8	-6.5%

use of LEDs, thus triggering potential benefits for the plants (Brazaitytė et al., 2006). The lack of extensive trials along with the diversity of horticultural species and the high cost of the luminaires and inefficiencies delays their integration in the current growing systems (Whitelam and Halliday, 2007; Trouwborst et al., 2010; Nelson and Bugbee, 2014). The use of LED luminaires is partly integrated in the greenhouse control systems, and has the potential of passing significant savings to the growers (Massa et al., 2008; Morrow, 2008).

Little is known about the physiological performance of ornamental plants grown under LED lighting. Furthermore, not many studies focus on a variety of plant species; thus, making general statements and recommending light recipes for specific species without thorough examination is insufficient (Ouzounis et al., 2015). In addition, given that LED luminaires emit less heat, there is also lack of knowledge about the lower leaf temperatures and the effect on plant growth.

The aim of this experiment was to evaluate the use of

conventional HPS lamps in comparison to commercial LED luminaires in a standard greenhouse using different species and cultivars during the winter period and early spring. The objectives were to (1) characterize the effect of LED lighting versus HPS lighting on developmental characteristics in roses and campanulas, and (2) identify the energy use differences between the HPS and LED lamps.

Materials and methods

Four cultivars of potted roses (*Rosa hybrid* L. 'Escimo', 'Apache', 'Pearl', and 'Scarlet') and two cultivars of campanula (*Campanula portenschlagiana* 'Blue Get Mee' and 'Blue Wonder') were grown in two identical greenhouse compartments (38 m²) located at Aarhus University, Årsløv, Denmark (lat. 55.309°N, long. 10.439°E). One compartment had light-emitting diodes installed (LED; Fionia Lighting A/S, Sønderød, Denmark), while the other compartment was equipped with high pressure sodium lamps (HPS, GreenPower Plus, 400W,

FIGURE 1. Plant height (A, C) and number of flowers and buds (B, D) of four pot rose cultivars grown in two greenhouse compartments, where the supplemental lighting sources were high pressure sodium (HPS; open columns) lamps or light emitting diodes (LEDs; closed columns). The plants were grown during the winter period (1st batch: 9 January – 8 February, 2nd batch: 13 February – 26 March), when solar irradiance is low. Values are the means of 12 plants $\pm$ SEM. Means followed by different letters indicate significant differences at P-values < 0.5 (comparison within treatments).

FIGURE 2. Leaf fresh weight (A, D), stem fresh weight (B, E), and total fresh weight (C, F), of four pot rose cultivars grown in two greenhouse compartments where the supplemental lighting sources were high pressure sodium (HPS; open columns) lamps or light emitting diodes (LEDs; closed columns). The plants were grown during the winter period (1st batch: 9 January – 8 February, 2nd batch: 13 February – 26 March), when solar irradiance is low. Values are the means of 12 plants $\pm$ SEM. Means followed by different letters indicate significant differences at P-values < 0.5 (comparison within treatments).

FIGURE 3. Leaf dry weight (A, D), stem dry weight (B, E), and total dry weight (C, F), of the four pot rose cultivars grown in two greenhouse compartments where the supplemental lighting sources were high pressure sodium (HPS; open columns) lamps or light emitting diodes (LEDs; closed columns). The plants were grown during the winter period (1st batch: 9 January – 8 February, 2nd batch: 13 February – 26 March), when solar irradiance is low. Values are the means of 12 plants $\pm$ SEM. Means followed by different letters indicate significant differences at P-values < 0.5 (comparison within treatments).

Philips, Eindhoven, The Netherlands). In the LED lighting, the proportion of blue light is 12.4%, while that of red light is 87.6%. The intensity at plant top level was $85 \pm 5 \mu\text{mol m}^{-2} \text{s}^{-1}$ and $75 \pm 5 \mu\text{mol m}^{-2} \text{s}^{-1}$ for the HPS and LED, respectively.

The potted roses were obtained from a commercial nursery (Rosa Danica, Marslev, Denmark) after second cutting and with four cuttings in a 10.5-cm pot. Just after arrival, 250 plants of each cultivar were placed in two separate plots. Later, according to growth and weather, the frequency was increased to twice a day. They were spaced to 30 plants m^{-2} , approximately after four weeks. Two consecutive batches of roses were imposed. The 1st batch was grown between 10 January and 14 February 2012 (harvest day), while the 2nd was grown from 13 February to 23 March 2012 (harvest day). The two cultivars of campanula 'Blue Wonder' and 'Get Mee' were placed in the same compartments as the roses in blocks of approximately 60 plants, with a density of 78 plants m^{-2} . Later they were spaced to 30 plants m^{-2} . Plants were watered once a day with a nutrient solution consisting of 185 ppm N, 27 ppm P, 171 ppm K, and 20 ppm Mg, plus micro-nutrients. The 1st batch was grown between 9 January and 7 February 2012 (harvest day), while the 2nd was grown from 9 January to 9 March 2012 (harvest day).

For both species, morphological and developmental (destructive and non-destructive) characteristics were recorded, namely plant height, leaf area, percentage of yellow leaves, number of flowers and buds, leaf and stem fresh and dry weight (above ground weight).

The climate in the two greenhouse compartments was controlled by a Senmatic climate computer (Senmatic, Sønderød, Denmark). Temperature was 24°C and 18°C during the day and night, respectively. Supplementary CO₂ was supplied at a level of 800 ppm. Shade curtains were drawn at irradiance over 600 watts. Supplementary light was on from 02:00 am to 10:00 pm (20 h photoperiod) when the irradiance was lower than $140 \mu\text{mol m}^{-2} \text{s}^{-1}$. The heating of each compartment was monitored by infrared leaf temperature sensors (Testo, Lenzkirch, Germany), and regulated by the climate computer aiming at maintaining equal tissue temperature in the treatments. Due to higher radiation from the HPS lamps, the ratio between heating from under the benches and above the benches differed (Table 1, Figure 5). More heating from above in the LED treatment was required to reach the same tissue temperature as in the HPS compartment. Use of electricity as well as use of energy for heating was monitored manually on a daily basis in both treatments.

FIGURE 4. Plant height (A), above ground dry weight (B), and number of flowers (C), of two campanula cultivars ('Blue Wonder' and 'Blue Get Mee') grown in two greenhouse compartments, where the supplemental lighting sources were high pressure sodium (HPS; open columns) lamps or light-emitting diodes (LEDs; closed columns). The plants were grown during the winter period (9 January – 9 March 2012), when solar irradiance is low (2nd batch). Values are the means of 12 plants $\pm$ SEM. Means followed by different letters indicate significant differences at P-values < 0.5 (comparison within treatments).

The energy use in kWh for lamps and for heating (below/above) was recorded on a daily basis. To secure that leaf temperature was maintained at the same level, the top heating system was allowed to increase if needed to correct for reduced leaf temperature.

FIGURE 5. Cumulative energy use of supplemental lighting (A) and heating (B) in two greenhouse compartments where the light sources were either light-emitting diodes (LEDs) or high-pressure sodium (HPS) lamps. Energy use was recorded on a daily basis by a climate computer.

Results

In general, the results showed relatively small differences between the treatments. The 1st batch of roses was grown between 10 January and 14 February, while the 2nd batch was grown from 13 February until 23 March. For the 1st batch of roses, plant height values were higher in the HPS treatment for all four ('Escimo', 'Apache', 'Pearl', and 'Scarlet') cultivars (Figure 1A), but statistically significant only for 'Escimo', 'Pearl', and 'Scarlet'. The number of flowers and buds did not differ among treatments for any of the cultivars and in both batches (Figure 1B). Leaf fresh and dry weight was substantially higher for HPS only for 'Scarlet' in both batches (Figures 2A and D, and Figures 3A and D). Stem fresh and dry weight for the 1st batch was also higher for 'Escimo', 'Pearl' and 'Scarlet' (Figures 2B and 3B); no difference was observed in the 2nd batch (Figures 2E and 3E). Total fresh weight was higher and substantially different in the HPS treatment for 'Pearl' and 'Scarlet' in the 1st batch (Figure 2C), while no difference was observed in the 2nd batch (Figure 2F). Similarly, total dry weight was higher and statistically different for HPS lamps only for 'Scarlet' for both batches (Figures 3C and F).

The 1st batch of campanulas was grown between 9 January and 7 February, while the 2nd batch was grown from 9 January until 9 March. For the 1st batch there was no difference for both 'Blue Wonder' and 'Blue Get Mee' regarding plant height, above ground dry weight, and number of flowers (data not shown). For the 2nd batch, plant height was not affected (Figure 4A). Above ground, dry weight was higher and statistically different only for 'Blue Wonder' (Figure 4B), but the number of flowers was higher for the HPS treatment for both cultivars (Figure 4C).

Since the set points for supplemental lighting were identical in the two compartments the light period was identical and the LED lamps used 40% of the energy supplied to the SONT lamps in the period (Table 1, Figure 5). The energy used for heating was identical for the bottom heating but increased by 100% on average resulting in an average heat energy increase (in kWh) of 40–50%, depending on the outside weather, which was unusually cool in 2012.

Discussion

Light is one of the most important environmental cues for plant development, and as such affects growth and morphogenesis throughout the whole year (Whitelam and Halliday, 2007). There are numerous examples in the literature on plant morphological responses to LED

lighting, more for edible plants than ornamentals. Regarding ornamentals, previous studies on roses have shown that increased blue/red ratio from LEDs increased leaf biomass, decreased leaf area and shoot biomass, and had no effect on flowering (Terfa et al., 2012a, b). Ouzounis et al. (2014) demonstrated that supplemental monochromatic red light and bichromatic red/blue (80% red/20% blue) increased plant height as well as leaf area more than a bichromatic 60% red/40% blue combination in *Rosa hybrida* 'Scarlet', while all three light treatments increased total fresh and dry weight compared to a white LED lighting. In the same study, no difference was found in the number of green or colored buds, indicating no effect on flowering. In our case in roses, in both batches, the number of flowers and buds was also not affected by the treatments, thus in accordance with the previous studies. The cultivar 'Apache' is a small flowering hybrid and 'Scarlet' is a large flowering hybrid with slightly different requirements to the growth environment; the large flowering varieties are regarded as being more sensitive to low leaf temperatures. Although no significant differences were seen regarding the number of flowers and buds in roses, the HPS grown plants were 2–4 days earlier irrespective of cultivars.

Plant growth and morphogenesis is affected by both red and blue light (Whitelam and Halliday, 2007; Sager and McFarlane, 1997). The photosynthetic apparatus is mostly affected by red light (Saebo et al., 1995) while blue light strongly affects photomorphogenesis, chlorophyll formation and stomata opening (Dougher and Bugbee, 1998). Plant height (stem elongation) is therefore affected by different combinations of red and blue, as blue light plays an important role since it is required for a functional photosynthetic and physiological operation (Hogewoning et al., 2010). Far-red light also affects elongation (red and far-red light absorbed by the phytochrome) by altering the red/far-red ratio (Sager and McFarlane, 1997; Casal, 2013; Chen et al., 2004); the red/far-red ratio also affects flowering but in our case we did not observe any differences as mentioned before, probably because the amount of far-red is totally absent in the blue/red combination and very limited in the HPS lamps (area after 700 nm). In our case the traditional HPS lamps had higher impact on stem elongation (also depicted in the stem dry weight in the 1st batch), indicating that a full spectrum causes greater elongation compared to a bichromatic red/blue LED combination with a relatively increased proportion of red light (88%). Increased proportion of red in

FIGURE 6. Diurnal leaf temperatures of *Rosa* 'Scarlet' (A) and *Campanula* 'Blue Wonder' (B) plants grown in two greenhouse compartments where the supplemental lighting sources were high-pressure sodium (HPS; solid line) lamps or light-emitting diodes (LED; dashed line). The data are from a single day (1 February 2012).

the light spectrum is known to suppress elongation. It shifts the red/far-red light absorbing phytochrome photoreceptor into its biologically active state, increasing its level in the total quantity of phytochromes (Li et al., 2011). It is known that the ratio of active and inactive phytochrome influences a variety of physiological process such as flowering time and elongation growth (Folta and Carvalho, 2015). Increased proportion of active phytochrome reduce elongation growth by suppressing growth promoting transcription factors such as phytochrome interacting factors (PIFs), which in turn suppress downstream signaling events related with increased elongation such as auxin synthesis and signaling (Chen et al., 2004). The situation was similar for leaf dry weight, but differences were only shown in 'Scarlet', indicating once more the species-dependent effect. Similarly, only 'Scarlet's' biomass was favored under HPS lighting, for both batches, pinpointing that a full spectrum is a better option for increasing total above ground biomass. The reduced biomass and delay in flowering time in roses under LED is also may be due to reduced leaf temperature. Leaf temperature was on average 2°C lower in plants grown under LED compared to HPS grown plants (Figures 6 and 7). The number of yellow leaves was in general higher (but not for all species significant) for the HPS lamps in the 1st batch, with only 'Scarlet' showing a prominent effect for HPS in both batches, which is likely to be due to internal shading of the plants.

In campanulas, LED lighting did not affect plant height at all for both batches, but since the number of flowers was higher in the 2nd batch under HPS, this indicates that LED lighting is not optimal for flowering compared to a full light spectrum. The above-ground dry weight was favored in the 2nd batch, on the contrary with previous results where red/blue LED lighting did not affect dry mass (Ouzounis et al., 2014). The effect was not apparent for 'Blue Get Me' in the 2nd batch, since the plants were enriched with natural light, however this was not the case with 'Blue Wonder', indicating cultivar dependence.

LED lamps used 60.4% less electricity compared to HPS (Table 1, Figure 5), with the total amount of electricity use reaching 300 kWh m⁻² for HPS, while LEDs reached only 119 kWh m⁻². The additional energy use for heating, though, changed the total energy use with the LED lamps finally consuming only 6.5% less energy compared to HPS (Table 1, Figure 5). This marginal economic gain is not totally in accordance with the study from Nelson and Bugbee (2014), who compared mainly U.S.-produced lamps (HPS and LED

units that had at most photon efficiency $\leq 1.7 \mu\text{mol W}^{-1}$. In Denmark and other northern European countries, independent measurements have shown efficiencies of commercially available Danish and Dutch LED units reaching 2.2–2.4 $\mu\text{mol W}^{-1}$, while the new HPS lamps of 1000W show up to 2.1 $\mu\text{mol W}^{-1}$ (C. Dam-Hansen and S. Pearson, pers. commun.). These new LED units are fully implementable in commercial use since their light distribution is equal or better than that of HPS. The option to use selected wavelengths makes LEDs more suitable for plant production than the current HPS lamps (Schuebert and Kim, 2005) but a direct replacement has been discouraged due to financial restrictions. The pay-back time now, though, seems more realistic as current energy prices drop and LED fixtures allow for dynamic output with regard to spectra and intensity.

It is worth noting that there was a gradual drop in the electricity use for both HPS and LED from January to March. Indeed, electricity consumption dropped 24.2% (from 111 to 84.1 kWh m⁻²) and 24.4% for HPS and LEDs, respectively. Similarly, the total energy use (taking into account the energy use for heating in kWh m⁻²) dropped 29.4% in HPS lamps, while in LEDs the drop was 30.1% (Table 1, Figure 5). The reduced energy use from January to March is also reflected in plant performance. Indeed, the supplemental light effect of HPS or LEDs was very limited or even nullified on the batches harvested in March as natural light was gradually increasing in the spring, making it the predominant light source with plants receiving enough sunlight that satisfies the requirements for plant growth and development. Another possible reason for limited effects could also be the intensity of both HPS and LED lamps, not even reaching 100 $\mu\text{mol m}^{-2} \text{s}^{-1}$ at plant height, which however is a normal installation level in commercial ornamental plant production, even though the light distribution in the case of LED fixtures is better than HPS. In addition, the experiment shows a reduced electricity use of 60.4% and an increased energy use for heating of 37.5% for LEDs compared to HPS (Figure 5). However, since the costs of electricity per kWh is higher than the cost of heat per kWh, the experiment proves that high output LED has reached a stage that results in substantial energy saving potential especially on crops that do not require high leaf temperatures.

In conclusion, the effect of supplemental LED lighting (mostly decrease in plant height and stem fresh and dry weight) on roses and campanulas was present but limited in February, while it was attenuated or absent in March, due

FIGURE 7. Average daily leaf temperatures of *Rosa* 'Scarlet' (A) and *Campanula* 'Blue Wonder' (B) plants grown in two greenhouse compartments where the supplemental lighting sources were high pressure sodium (HPS; solid line) lamps or light emitting diodes (LED; dashed line). The data are from 17 January to 20 February 2012.

to increasing natural lighting. It should also be noted that the differences were species- and cultivar-dependent. This should be an alert to growers when choosing a specific ornamental species and they should expect different cultivar responses and accordingly adjust light recipes. Furthermore, there were substantial savings in electricity use of LED lighting, although the overall energy use (electricity plus heating) was comparable. As current energy prices drop and LED fixtures allow for dynamic output with regard to spectra and intensity, an investment with a realistic payback time is nowadays possible.

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