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Artificial light from light emitting diodes (LEDs) with a high portion of blue light results in shorter poinsettias compared to high pressure sodium (HPS) lamps

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ABSTRACT

Strict control of morphogenesis is essential in production of potted poinsettia. Commonly, this is obtained by the use of plant growth retardants (PGRs), often in combination with early morning temperature drops. Due to negative effects on human health and the environment, the use of PGRs is becoming restricted. Also, energy-saving growth regimes and periods of high temperatures limit effective use of temperature drops. In the present study the use of a high proportion of blue (B) light provided by light emitting diodes [LEDs, 20% blue (B), 80% red (R)] was compared with traditional high pressure sodium (HPS) lamps (5% B) providing similar phytochrome photostationary state to produce compact poinsettia plants. Both in the greenhouse and growth chamber, all cultivars were 20–34% shorter for LED compared to HPS grown plants. Also, leaf and bract area as well as chlorophyll content and total dry matter accumulation were lower under LED. The LED did not delay bract color formation, visible cyathia and flowering compared to HPS, and no difference in post production performance (cyathia/bract abscission or necrosis) between the two light treatments was found. The effect of end of day-red (EOD-R) lighting combination with LED and HPS supplemental lamps during the photoperiod in the greenhouse was also investigated. Reduced stem extension (13%) was observed under HPS only and for one of the two cultivars tested, whereas under the LED regime, there was no effect of EOD-R lighting.

1. Introduction

Poinsettia (*Euphorbia pulcherrima* Willd. ex Klotzsch) is a very popular and economically highly significant potted plant in North America, Europe, Asia and Australia (Ecke et al., 2004). In northern Europe, poinsettias are commonly produced during autumn in greenhouses with the use of supplementary photosynthetic lighting due to low natural solar radiation. The most common light source is high pressure sodium (HPS) lamps which has a high emission of photosynthetic active radiation (PAR) and a high electrical efficiency but contain only 5% blue (B) light (400–500 nm) which is low compared to natural sun light (18% B). Different plant growth regulators (PGRs) such as chlormequat, daminozide or paclobutrazol are commonly used to inhibit the elongation growth in order to grow compact plants. However, PGRs have some negative impacts on human health and the environment, and are expensive and time-consuming to apply (De Castro et al., 2004; Sørensen and Danielsen, 2006). Thus, to control elongation growth of poinsettias different alternative strategies like manipulation of temperature, light quality and light duration have previously been tested (Clifford et al., 2004; Cockshull et al., 1995; Myster and Moe, 1995; Ueber and Hendriks, 1992). Until now a combination of PGRs and early morning temperature drop treatment have been the most common methods in commercial production in northern areas (Myster and Moe, 1995). Depending on the temperature regime, temperature drop in the morning can reduce the elongation in poinsettia by up to 25% compared to constant temperatures (Moe et al., 1992a). However, the implementation of a temperature drop treatment may be difficult early in the autumn when the temperature and solar radiation are high.

Moreover, energy saving in greenhouse production has received much attention lately (Körner and Van Straten, 2008). Climate strategies where ventilation is avoided and the growing temperature follows more the natural variation in day (DT) and night temperatures (NT) to reduce energy consumption are of current interest (Blanchard et al., 2011; Fitz-Rodríguez et al., 2010; Lund et al., 2006; Markvart et al., 2007). However, energy-saving growth regimes with reduced ventilation limit the use of temperature

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drops. Thus, there is interest in alternative height control strategies and especially focus on light quality.

Physiological knowledge on the action of photoreceptors involved in plant morphogenesis is available in many plant species (Smith, 2000). The main light receptors known to have prominent effects on plant morphology are the B light absorbing cryptochromes and the red (R) and far-red (FR) light absorbing phytochrome light receptors. Phytochromes are inter converted between a biologically inactive (P_R) and an active form (P_{FR}) depending on the light quality (Smith, 2000). However, the phytochrome responses vary with plant species, cultivar, age, irradiance, spectral quality and temperature. Low levels of FR light in the spectrum or a high ratio between R and FR commonly result in short, compact plants (Mata and Botto, 2009). Plants are usually more sensitive to R and FR light at the end of the day (EOD), and ten to sixty min of EOD-R light may be as effective as a high R/FR ratio during the whole lighting period (Hisamatsu et al., 2005; Ilias and Rajapakse, 2005; Symons and Reid, 2003). Also, cryptochromes are known to affect stem extension, and a variety of plants respond to B light by suppressing the shoot elongation (Hoenecke et al., 1992). However, the opposite effect with increased shoot elongation under pure B light compared to R light has also been reported in a number of species such as *Salvia* and marigold (Heo et al., 2002).

Another reason for the interest in utilizing light quality to modulate plant growth and morphology is the recent development of light emitting diodes (LEDs) as a lighting source in greenhouse production (Barta et al., 1992; Bula et al., 1991). Such small diodes can easily be placed close to the canopy and can be used to apply narrow-band light spectrum to the plants. Specific requirements for light spectral distribution for specific processes like morphogenesis, photosynthesis, chlorophyll and anthocyanin synthesis have been determined in different species (Robin et al., 1994a, 1994b; Stutte, 2009; Tripathy and Brown, 1995). However, little information is available on the effects of such light regimes on the growth of poinsettia, and no photoreceptors are until now identified in this species. Experiments with selective plastic films absorbing FR light or manipulation of the R/FR ratio have indicated that the morphology of poinsettia is responsive to the R/FR ratio (Clifford et al., 2004). On the other hand, experiments with a B deficient environment under spectral filters have suggested that B light does not play a significant role in controlling stem extension in this species (Clifford et al., 2004; Mortensen and Strømme, 1987). However, to the best of our knowledge, there are no studies where poinsettia is grown with increased B light.

The objective of this study was to examine the use of LED light as a tool to control elongation of poinsettias as well as on flowering time and postharvest quality. Specifically, the aim was to test if LED light with a higher portion of B light (20% B) than the commonly used HPS lamp (5% B) with similar phytochrome photostationary states (PSS), can suppress elongation. Further, to evaluate the effect of manipulating the phytochrome apparatus under these light conditions, poinsettias were exposed to low fluence rate R light in the end of the day (EOD-R).

2. Materials and methods

2.1. Plant material and pre-cultivation

Cuttings of *Euphorbia pulcherrima* Willd. ex Klotzsch (poinsettia) cultivars 'Christmas Spirit', 'Christmas Eve' and 'Advent Red' with 6–7 leaves rooted in Jiffy-7 (G3 Ljones Gartneri AS, Tørvikbygd, Norway), were potted in 13 cm plastic pots filled with *Sphagnum* peat (Veksttorv, Ullensaker Almenning, Nordkisa, Norway). The plants were kept in a growth chamber at 20 °C with an average relative air humidity of 70 ± 5%, corresponding to an average of 0.7 kPa

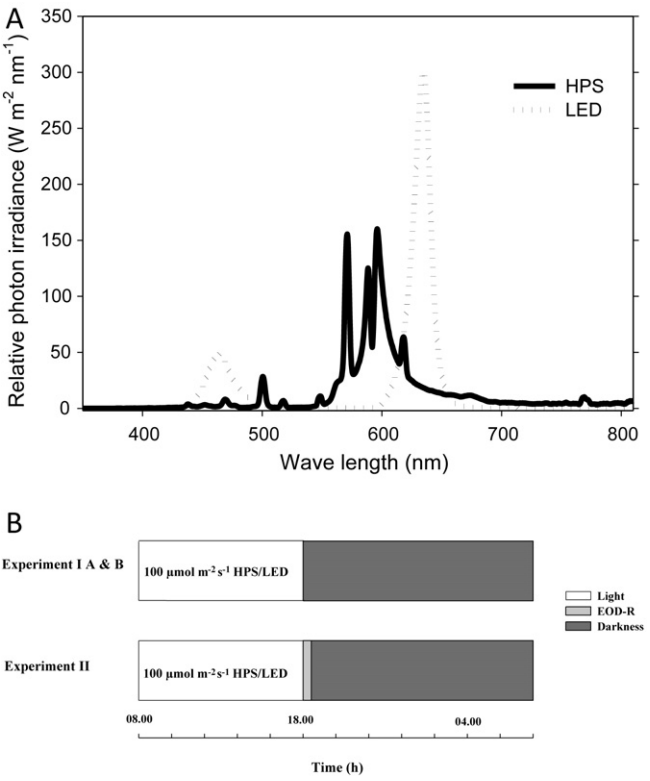

Fig. 1. (A) Light spectra of HPS (LU400/XO/T40) and LED lamps (SoLa-co round high power 162 W LED-light), used in the experiments. (B) Schematic illustration of the light conditions in experiment I (A and B) and II. In experiment II, 5 μmol m^{-2} s^{-1} of R-light was given at the end of the day for 30 min in greenhouse.

water vapor deficit (VPD), under 18 h photoperiod provided by cool white fluorescent (OSRAM L 58 W/640, Munich, Germany) at a photosynthetic photo flux density (PPFD) of 80–90 μmol m^{-2} s^{-1} for 6 weeks. The plants were pinched up to 3–4 leaves, and when the new shoots were 0.5–1 cm long, plants were transferred to different light quality treatments in growth chambers or greenhouse compartments. Three shoots were allowed to grow per plant. The plants were watered daily during the whole experimental period with a commercial nutrient solution [red superba and calcinit (Yara, Oslo, Norway)] with an electrical conductivity (EC) of 1.5 mS cm^{-1} and a pH of 5.6–5.8.

2.2. Experimental set-up and light quality treatments

Two experiments (experiments I and II) were performed at Centre for Plant Research in Controlled Climate, Norwegian University of Life Sciences, Ås, Norway (59°39′47″N, 10°47′38″E) from September to December in 2009 and 2010. In experiment I, we compared HPS and LED (Fig. 1A and B) as supplementary lighting in the greenhouse (experiment I A) and in closed growth chambers (experiment I B). Also, an experiment was performed to test the effect of EOD red light (EOD-R) in combination with HPS and LED as supplemental lighting (experiment II). In experiment I A 'Advent Red' (2009) and 'Christmas Eve' and 'Christmas Spirit' (2010) were supplemented with a PPFD of 100 ± 20 μmol m^{-2} s^{-1} for 10 h daily (14 h darkness) with HPS lamps containing 5% B (LU400/XO/T/40; General Electric Company, NelaPark, Cleveland, Hungary) or light emitting diodes (LEDs) containing 20% B (wavelength 450–500 nm, peak at 465 nm) and 80% R (wavelength 600–700 nm, peak at 630 nm) (Round LED-light 162W, VA–24150T, SoLa-co, Grimstad, Norway) as supplemental lighting. The spectra for the lamps were measured with a spectrophotometer (OceanOptics, model-SD2000,

USA) (Fig. 1A). The phytochrome photostationary states (PSS), was calculated according to Sager et al. (1988) by multiplying the irradiance at each wavelength against the relative absorption for each form of phytochrome and were 0.89 and 0.85 for LEDs and HPS, respectively. The lamps were turned on in the morning (08.00 am) and turned off right after the black cloth was pulled on in the evening (18.00 pm). The average natural solar radiation during the experimental periods (September–December) were 9.3 and 9.5 mol m^{-2} d^{-1} for 2009 and 2010, respectively (Meteorological data from Ås, Norway). In experiment I B, 'Christmas Eve' and 'Christmas Spirit' were grown in growth chambers with similar HPS and LED lamps as described above (Fig. 1A) at a PPFD of 100 ± 20 μmol m^{-2} s^{-1}.

In experiment II (greenhouse 2009), the cultivars 'Advent Red' and 'Christmas Eve' were grown in a greenhouse compartment with LED or HPS (as described above, Fig. 1A) as supplemental lighting with and without 30 min of low irradiance (5 μmol m^{-2} s^{-1}) R light at the end of day (EOD-R) provided by small LED strings placed close to the plant canopy (LED power drivers, peak 630 nm, 177358/4908, 24 VDC/max 10W, Philips, Eindhoven, The Netherlands). The EOD-R treatment from 18.00 to 18.30 h was given right after the black cloth was pulled (Fig. 1B).

The temperature in the greenhouse and the growth chambers was 21 ± 2 °C and the relative air humidity (RH) was 70 ± 5%. In the growth chambers the CO_2 concentration was at ambient level (400 ppm) whereas in the greenhouse compartments the air was enriched to 800 ppm pure CO_2 (Yara, Oslo, Norway). The climate data were recorded in 5 min intervals by a computer control system (Integro 3, Priva, Ontario, Canada). The irradiance was measured at the plant canopy level using a LI-COR Quantum/Radiometer/Photometer (Model LI-250, Li-COR, Lincoln, Nebraska, USA).

2.3. Growth analysis and postharvest quality testing

The length from the base of the stem to the shoot apical meristem was measured on each shoot once a week or every two weeks. At flowering (cyathia formation), growth analysis was performed on all three shoots of 10 greenhouse-grown plants, for each cultivar in each experiment. The leaf length of four mature leaves per stem and the stem diameter at the middle of each shoot was measured. The number of leaves and bracts were counted and the average internode lengths were calculated by dividing stem length by the number of leaves. Bracts were defined as transition leaves which had formed red color and were counted if the length exceeded 3 cm (petiole + bract). Leaf and bract area was measured by a leaf area meter (Model 3100, LI-COR). Fresh and dry weight of stem, leaves and bracts were recorded after drying at 65 °C until a constant mass was reached. Total dry matter (DM) was calculated from the total sum of dry weight of stem, leaves and bracts. Specific leaf and bract area (SLA and SBA, respectively) were determined from area/dry weight for each of them. Total chlorophyll content was measured on the middle leaf of the three shoots on each plant by a chlorophyll content meter (Model CL-01, Hansatech Instruments, Norfolk, England). In experiment I A, post harvest quality was tested on 5 plants of the 'Christmas Spirit' and 'Christmas Eve' for 5 weeks. The temperature in the test room was kept at 21 °C and RH at 30–40%. An irradiance of 10 μmol m^{-2} s^{-1} for 12 h per day was provided by fluorescent tubes (Philips Master TL-D 58W/830, Holland).

2.4. Statistical analysis

Effects of treatments on growth, morphology and length of shoots were analyzed by analysis of variance (General Linear Model procedure) and Tukey's pair wise comparison test ($p < 0.05$) using Minitab Version 16 (Minitab Inc., State College, PA, USA).

3. Results

A difference in growth pattern between the light treatments appeared after about 5–6 weeks for all cultivars both in the greenhouse and in growth chambers (Figs. 2 and 3). At the marketing stage after about 12 weeks of treatment, the total shoot length of all the cultivars tested was significantly reduced under LED. 'Christmas Spirit' showed the strongest response (Figs. 2–4) with a reduction in plant height by 34% both in the greenhouse and growth chambers under LED compared to HPS, whereas 'Christmas Eve' showed 27% and 21% height reduction, respectively. 'Advent Red', which was tested only in the greenhouse, showed a 20% height reduction.

In addition to a reduced shoot length, plants grown under LED had significantly shorter petioles, reduced leaf and bract area, resulting in reduced plant diameter and more compact plants, compared to HPS (Table 1 and Fig. 4). On average, petiole lengths were reduced by 36 and 37%, leaf area by 40 and 46%, bract area by 61 and 49% and stem diameter by 15 and 14% for 'Christmas Spirit' and 'Christmas Eve', respectively. The LED-grown plants also had significantly shorter and fewer internodes than the HPS grown ones (Table 1 and Fig. 5). The internode length was reduced by 24 and 17% and the number of internodes by 26 and 17% for 'Christmas Spirit' and 'Christmas Eve', respectively. 'Christmas Spirit' and 'Christmas Eve' showed a 17% and 30% decrease in chlorophyll content but a 43% and 35% decrease in total dry matter content respectively (Table 1). However, no significant difference was observed in the distribution of DM (%) in leaves, bracts and shoot between the two light treatments (data not shown). In 'Christmas Eve' the SLA and SBA was reduced 12 and 16% respectively in LED light compared to HPS (Fig. 6).

No significant difference in time to visible cyathia was observed between plants grown under LED and HPS either in the greenhouse or in growth chambers (data not shown). Visible cyathia were observed after about 9 weeks in both cases. Similarly, there was no significant difference in the keeping quality in the 'Christmas Eve' or 'Christmas Spirit' grown under LED and HPS. Only a small number of bracts abscised in 'Christmas Eve' under both light qualities but no bract necrosis or cyathia drop appeared during 5 weeks of testing (data not shown). Overall, no significant differences in post harvest quality parameters were observed between the plants grown under the two light qualities.

The effectiveness of an EOD-R treatment in reducing shoot elongation further was investigated in 'Christmas Eve' and 'Advent Red' grown under HPS and LED light under short day conditions. EOD-R light significantly reduced the height of 'Advent Red' by 13% when HPS was used as a supplemental lighting but had no effect on height under LED (Fig. 7). EOD-R had no significant effect of height on 'Christmas Eve' (Fig. 7).

4. Discussion

In the present study, a height reduction by 20–34% was achieved when poinsettia plants were grown under LED with a higher portion of B light (20%) than provided by the traditional HPS lamps (5% B). The internodes (17–24% reduction) and petioles (36–37% reduction) were shorter and the expansion of the leaves and bracts was reduced under LED compared to HPS, resulting in very compact plants (Table 1 and Figs. 2–4).

The phytochrome photostationary states (PPS) were 0.85 and 0.89 for the HPS and LEDs, respectively, indicating that mainly the blue light and not the PPS, was critical in regulating the stem extension growth (Sager et al., 1988; Stutte, 2009). This suggests that the

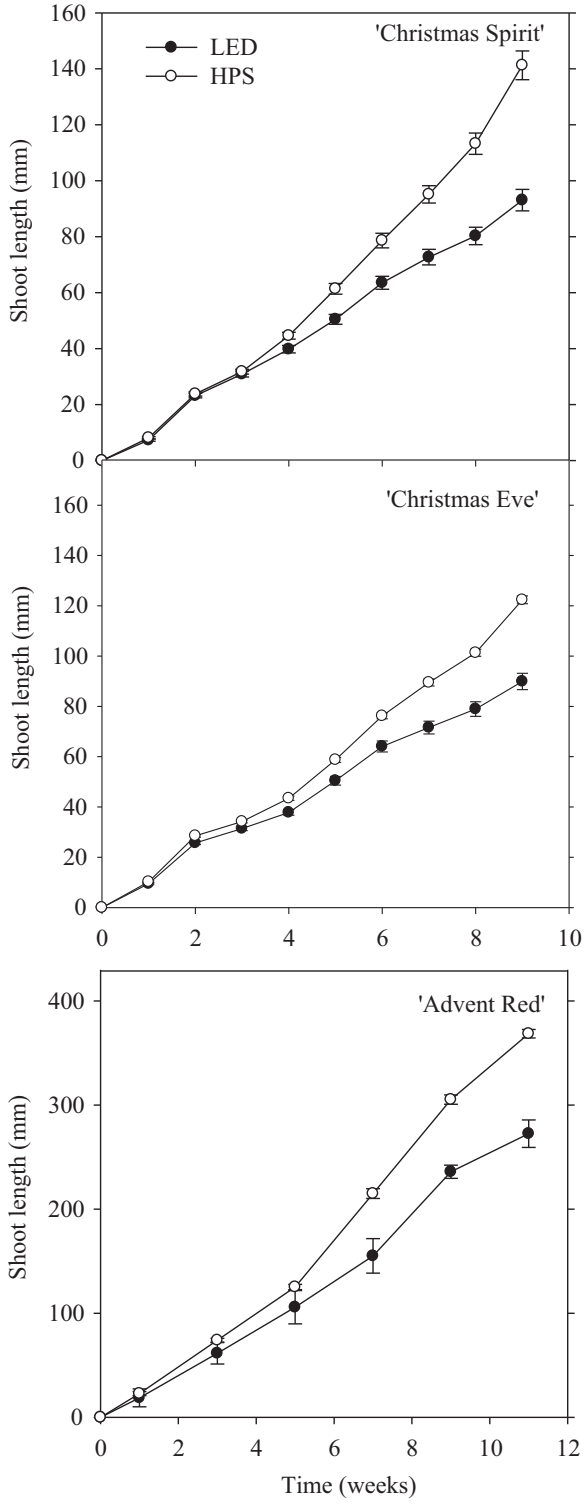

Fig. 2. Effect of LED light (20% B and 80% R) compared with HPS as supplementary lighting on shoot length of poinsettia 'Christmas Spirit' ($n = 45$), 'Christmas Eve' ($n = 48$) and 'Advent Red' ($n = 12$). HPS/LED was provided 10 h daily in a greenhouse compartment and black cloths were pulled in the evening to prevent natural light from the outside (14 h darkness). The average natural solar radiation during the experimental periods (September–December) was 9.4 mol m^{-2} d^{-1}. Vertical bars represent the ±SE (standard errors).

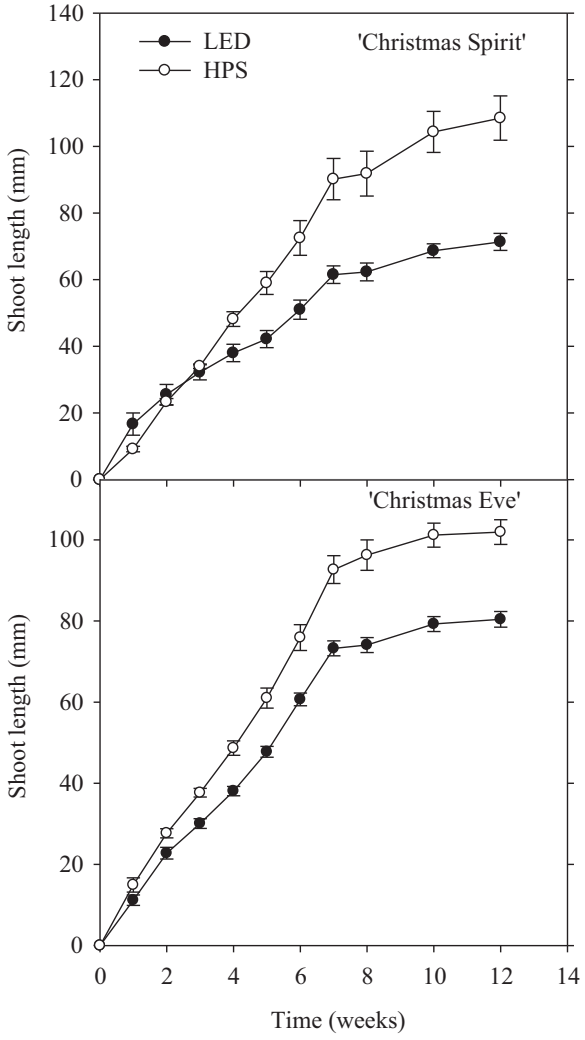

Fig. 3. Effects of LED light (20% B and 80% R) compared with HPS on shoot length of poinsettia 'Christmas Spirit' ($n = 6$) and 'Christmas Eve' ($n = 12$) under short day conditions (10 h) at an irradiance of 100 μmol m^{-2} s^{-1} in growth chambers. Vertical bars represent the ±SE (standard errors).

cryptochrome photoreceptors are important in the control of stem elongation of poinsettia. In earlier studies with the use of spectral films to manipulate light quality, it was claimed that B light did not play an important role in mediating stem extension of poinsettia (Clifford et al., 2004; Mortensen and Strømme, 1987). In those studies, no response or only a small promotion of stem extension was found under a B light deficient environment. However, the current study clearly shows that B light is effective in the control of stem extension of poinsettia when more B light is added to the environment.

B light suppression of petiole and stem extension as well as hypocotyl elongation have been demonstrated in a variety of horticultural plants species including soybean, pepper and lettuce (Brown et al., 1995; Hoenecke et al., 1992; Holmes and Schäfer, 1981; Schuerger et al., 1997; Wheeler et al., 1991). Typically, increasing B light decreases stem length down to a maximum threshold level (Wheeler et al., 1991). The amount of B light in the spectrum for maximum inhibition of stem extension of poinsettia is not known. An increase in B light from 5% to 20% in the current study reduced the stem extension extensively but it also reduced the relative chlorophyll content and the total DM accumulation (Table 1). It is probably not practical to increase the amount of blue light >20%.

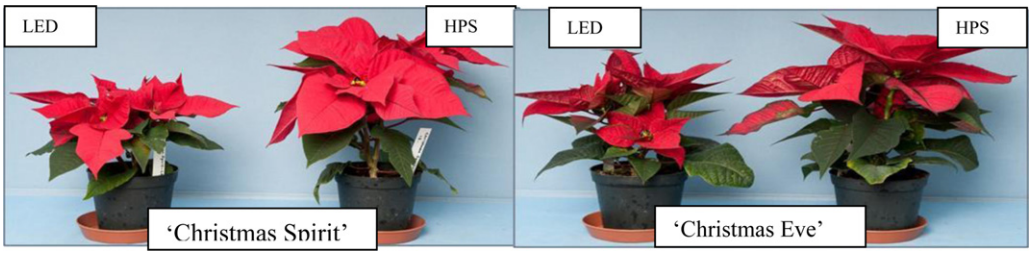

Fig. 4. Morphology of poinsettia grown under LED light (20% B and 80% R) and HPS as supplementary lighting (100 μmol m^{-2} s^{-1} for 10 h daily) in greenhouse compartments. Plants were grown at 21 °C, 70% relative air humidity and 800 ppm CO_2.

Table 1
Growth and morphology of poinsettia plants grown under LEDs (20% B and 80% R) or HPS as supplementary lighting (100 μmol m^{-2} s^{-1} for 10 h daily in 12 weeks) in a greenhouse compartments.

Growth parameter	'Christmas Spirit'		'Christmas Eve'	
	LED	HPS	LED	HPS
Shoot length (mm)	93.1 ± 3.8 a	141.3 ± 5.2 c	89.9 ± 3.3 a	122.4 ± 1.6 b
Relative chlorophyll content	16.6 ± 0.7 a	20.0 ± 0.8 b	14.6 ± 0.8 a	20.8 ± 0.7 b
Petiole length (cm)	2.8 ± 0.1 b	4.4 ± 0.1 d	2.2 ± 0.1 a	3.5 ± 0.1 c
Shoot diameter (mm)	5.3 ± 0.1 a	6.2 ± 0.1 b	5.5 ± 0.1 a	6.4 ± 0.2 b
Internode length (mm)	20.6 ± 0.8 b	27.2 ± 0.8 c	15.4 ± 0.6 a	18.5 ± 0.4 b
Total leaf area (cm^2)	148.1 ± 8.4 a	247.1 ± 12.1 c	112.9 ± 8.4 a	208.4 ± 11.1 b
Total bract area (cm^2)	79.7 ± 5.6 a	205.6 ± 9.4 b	183.4 ± 15.1 b	359.7 ± 17.1 c
Total dry matter (g)	1.6 ± 0.1 a	2.8 ± 0.2 b	1.8 ± 0.1 a	2.8 ± 0.1 b

Mean ± SE followed by non-similar letters within a parameter are significantly different at $p < 0.05$ according to Tukey's test. $n = 20–30$.

The total bract area was reduced by 50% or more under LED compared to HPS, and the expansion of the bracts was more reduced than the expansion of the leaves. The reduced bract size may lower the ornamental value and the marketability of some cultivars of poinsettia. Especially, the 'Christmas Spirit' developed small bracts under LED. To avoid reduction in bract expansion the B light proportion may be reduced in the later stage of the production during the active bract expansion phase. The use of LED technologies may thus be an effective method to optimize the different phases in the production of poinsettia.

No difference in time to open flowers was found between LED and HPS, showing that poinsettia tolerates LEDs with a high proportion of B light in the spectrum without negative effects on the time to the marketing stage. However, the plants grown under LED had developed fewer leaves and bracts at flowering than plants grown under HPS (Fig. 5), indicating a faster floral induction on a leaf number basis under increased B light. A similar response has been reported in the long day plant (LDP) *Arabidopsis thaliana* where either FR or B light is known to hasten the transition to flowering, while R delays it (Kenneth, 1992). In this species both phytochrome and cryptochrome light receptors are involved in the floral control (Simpson and Dean, 2002). However, less is known on the effects of B light on flower transition of short day plants (SDPs). Both the B light photoreceptor-and phytochrome-mediated pathways are probably involved in the flowering of poinsettia. A delay in time to the stage with visible cyathia was reported in poinsettia under selective films lacking FR light but no effects was found when the plants were grown in a B light deficient environment (Clifford et al., 2004). Although the HPS grown plants in the current study flowered at a higher leaf number, the time to visible cyathia or time to open cyathia was not significantly different between the different light treatments. Thus, the growth and development of the inflorescence was probably faster under HPS than the LED. The larger leaves with longer petioles probably resulted in a more effective light capturing and a higher potential for fast growth and development compared to the smaller leaves of compact LED-grown plants. Further, about 1.5 °C higher leaf temperature was measured under HPS compared to LED because of higher infra-red radiation exposed directly to the plants (results not shown) which may also have compensated for the extra leaves.

It should be noted that no significant difference was observed in the post production performance of poinsettia grown under LED and HPS. The plants were transferred directly from the greenhouse into the post harvest test room without any simulated transport or storage. The keeping quality of the plants was very good irrespective of the light treatment without cyathia drop or bract necrosis during the 5 weeks of testing. In earlier experiments where diurnal temperature manipulation was used to reduce stem extension a negative effect on the postharvest quality was found. After four weeks of testing under similar conditions as in the current study, all the cyathia abscised in the cultivars 'Lilo' and 'Starlight' (Moe et al., 1992a).

All cultivars tested were more compact under LED and the response to B light was similar in greenhouse compartments and growth chambers indicating that the natural light during the experimental periods (autumn) did not influence the response qualitatively. However, the shoot length showed a linear increase over time in the greenhouse, but a saturating response in the growth chamber experiment. The extra energy the plants get from the natural light in combination with the high CO_2 concentration in the greenhouse (800 ppm) probably contributes to the increased extension in the greenhouse experiment compared to the growth chamber. The magnitude of this effect of LED treatment is similar to or stronger than other height control strategies commonly used in the greenhouse industry. About 20–25% height reduction was found in poinsettia using FR-removing plastic filters, and up to 25% reduction has been demonstrated in temperature drop experiments (Clifford et al., 2004; Moe et al., 1992a, 1992b). In the current experiment, more B light did not delay flowering time like it has been observed when photoselective films or temperature manipulations were used as tools to control height (Mata and Botto, 2009; Moe et al., 1992a). Thus, supplementary LED lighting with

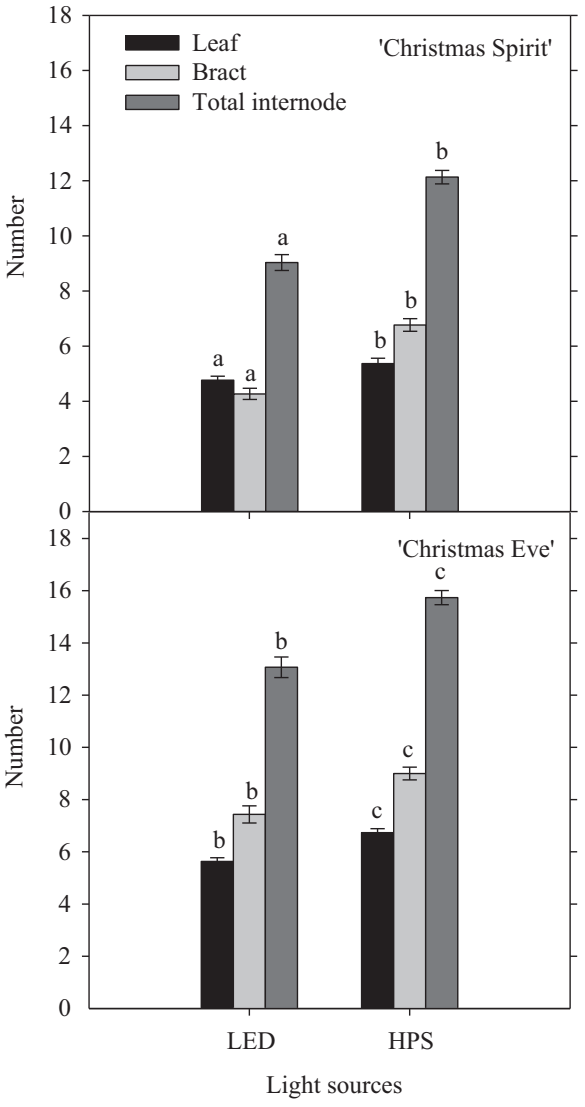

Fig. 5. Number of leaves, bracts and the total internodes (sum of leaves and bracts numbers) of poinsettia grown in greenhouse compartments with LED light (20% B and 80% R) or HPS as supplementary lighting at an irradiance of 100 μmol m^{-2} s^{-1} during a 10 h photoperiod. Vertical bars represent the ±SE (standard errors) (n = 30). Mean values with the same letter are not significantly different based on ANOVA followed by a Tukey's test at p < 0.05.

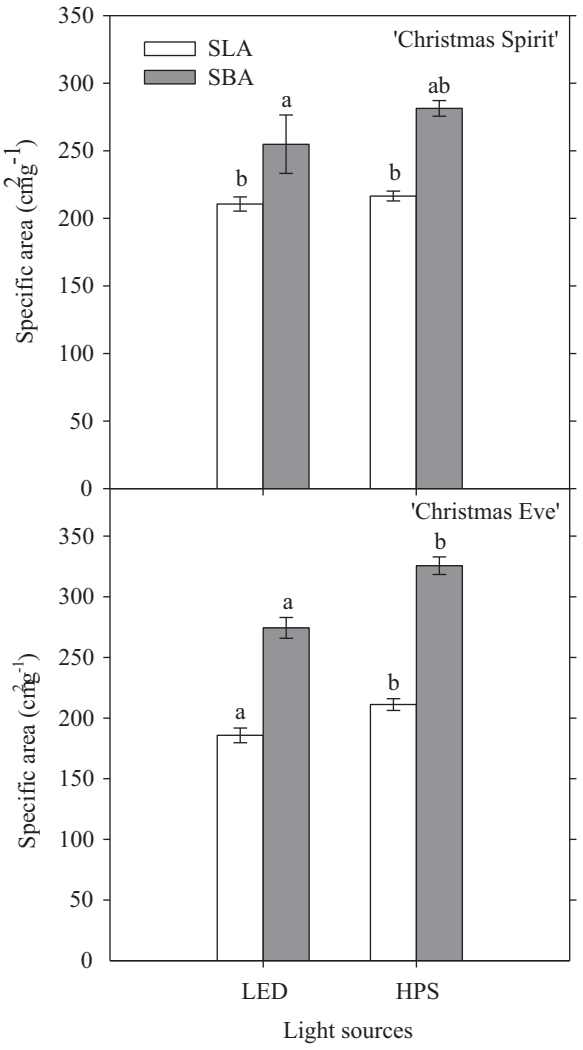

Fig. 6. Specific leaf area (SLA) and specific bract area (SBA) of poinsettia grown in greenhouse compartments under LED light (20% B and 80% R) or HPS as supplementary lighting at an irradiance of 100 μmol m^{-2} s^{-1} during a 10 h photoperiod. SBA and SLA were calculated from leaf or bract area divided by their respective dry weights. Vertical bars represent the ±SE (standard errors) (n = 30). Mean values with the same letter are not significantly different based on ANOVA followed by a Tukey's test at p < 0.05.

increased B light has a potential to be an effective method to control stem extension in commercial culture of poinsettia without quality reduction.

The use of EOD treatment with low intensity light (5 μmol m^{-2} s^{-1}) to control stem extension requires little energy. In the present study, EOD-R was found equally effective in one of the cultivars tested as the traditional temperature drop treatment when the supplemental light was provided by HPS (Fig. 7). Thus, EOD-R in combination with HPS supplemental light might possibly substitute the traditionally used temperature drop treatment. Others also reported on suppressive effects of EOD-R for species like *Petunia*, *Chrysanthemum*, tobacco and soybean (Ilias and Rajapakse, 2005; Kasperbauer, 1971, 1987; Rajapakse et al., 1993). The effect of EOD-R on poinsettia was somewhat weaker than the response to increased B light, and one of the cultivars tested ('Christmas Eve') did not respond to EOD-R either in the greenhouse (Fig. 7) or in chamber experiments (Islam, unpublished results). Others also report on variable results or no significant effect of EOD-R light treatment on poinsettia (Mata and Botto, 2009). This might be due to different sensitivity to light qualities in different species or cultivars as a consequence of differences in the action of photoreceptors. The differential light quality response might also be due to differential hormonal regulation of stem extension growth of poinsettia, but so far knowledge on this is limited. It is well known however, that both the phytochrome and the cryptochrome are involved in regulating the content of the plant hormone gibberellins (Hisamatsu et al., 2005; Zhao et al., 2007).

Since no effect of EOD-R was observed when LED was used as supplemental light, it is possible that the inhibition of the extension growth of poinsettia is saturated under a light spectrum with high B portions (Fig. 7). In contrast to the LED light source, the HPS contain low B light. The LEDs appear already to be saturated in inhibition of shoot elongation, and accordingly EOD-R does not result in further inhibition as it did when HPS was used as supplementary light (Fig. 7).

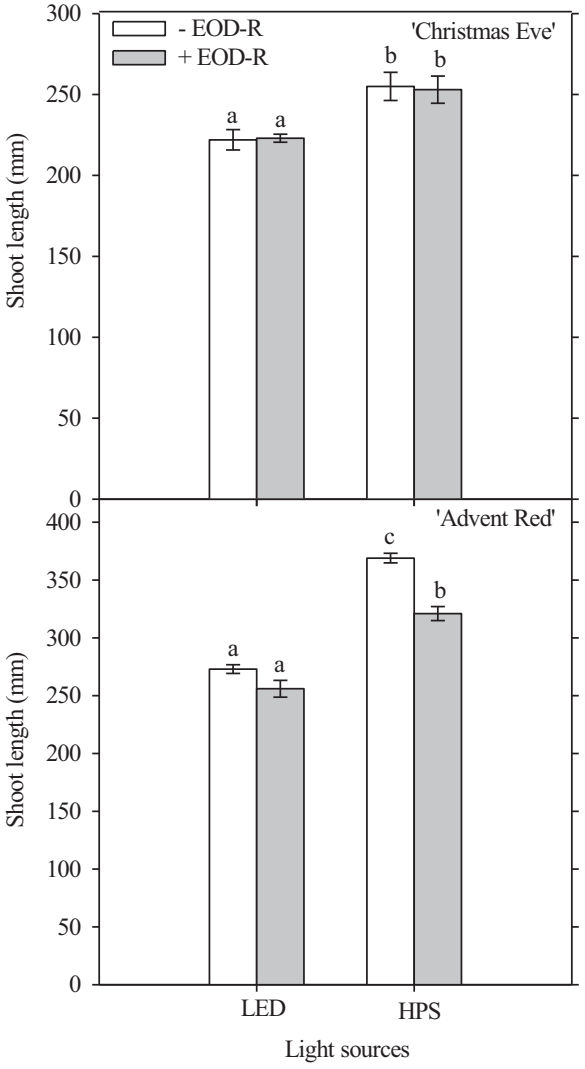

Fig. 7. Effect of 30 min end-of-day red light (EOD-R) at an irradiance of 5 μmol m^{-2} s^{-1} on poinsettia plant height grown in a greenhouse compartment under supplementary lighting with LED lamps (80% R and 20% B) or HPS lamps at 100 μmol m^{-2} s^{-1}. Vertical bars represent the ±SE (standard errors) (n = 12). Mean values with the same letter are not significantly different based on ANOVA followed by a Tukey's test at $p < 0.05$.

In conclusion, LED with a high proportion of B light was effective in reducing the stem extension growth of all the poinsettia cultivars tested compared to HPS. The plants were compact with 20–34% height reduction without any effect on the flowering response or post harvest quality. EOD-R light reduced shoot length by up to 13% in one of the cultivars tested when the supplemental light was provided with HPS (5% B) but had no effect under LED top light (20% B). This in generally shows that adding more B light to the spectrum by using LED light is more effective than manipulation of the phytochrome status at the end of the day.

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