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Development and Acclimatisation of Horticultural Plants Subjected to Narrow-Band Lighting

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Summary

Light-emitting diodes (LED) allow narrow-band light to be easily obtained and can be used for narrow-band lighting in plant cultivation, with possible effects on plant growth and development. This study examined use of narrow-band lighting of different wavelengths in the cultivation of ornamental pot plant (*Pelargonium* and *Petunia*), tomato (*Solanum lycopersicum*) transplants and sunflower (*Helianthus annuus*), either as sole light source in growth chambers, or as end-of-day (EOD) treatment in a greenhouse environment. Biometric measurements on plant growth and measurements of photosynthesis and stomatal conductance showed that when *Helianthus* was grown exclusively in blue light, stem elongation was greater than when it was grown exclusively in yellow, red, green or white light. Similar results were obtained when blue light was supplied in EOD treatments for *Petunia* and *Pelargonium* and for tomato. However, stem elongation was also high when red light was given as EOD treatment to tomato, whereas green light gave the least elongated plants in these conditions. Biomass production was generally not affected by the different EOD treatments. For *Helianthus* plants grown solely in monochromatic light, plant biomass production was highest in red light. For *Pelargonium*, photosynthetic rate was highest in blue light. It was concluded that plant response to different wavelengths is species-dependent and that EOD treatment with narrow-band lighting might be useful for plant growth regulation.

Key words. artificial light – *Helianthus* – light emitting diode – *Pelargonium* – *Petunia* photosynthesis measurement – *Solanum*

Introduction

The rapid development within light-emitting diode (LED) technology in recent years, with increasing light intensity and decreasing costs, has made this technology available for horticultural purposes (Morrow 2008). Among other benefits, LED technology offers the possibility of easily obtaining narrow-band lighting, with possible use in greenhouse crops. The impact on plant growth of narrow-band lighting has been examined in several studies. These show e.g. that blue light reduces shoot length in *Pelargonium*, compared with red, white or incandescent light (Appelgren 1991) and that blue light from metal halide lamps increases shoot length and internodal length in *Petunia* compared with high-pressure sodium lamps (Fukuda et al. 2002). Increased stem elongation has also been reported in eggplant grown under blue LED light (Hirai et al. 2006). Removing red and far-red light from natural sunlight by spectral filters also affects plant growth, with reduced stem elongation as a result (Rajapakse and Kelly 1992; Reddy and Rajapakse 1996). Monochromatic light may also have an influence on plant development when given in certain intervals or periods as a complement to white or natural light. For example, Shimizu et al. (2005, 2006) showed that blue LED light had an inhibitory effect on the elongation of *Chrysanthemum* when given as night interruption light.

End-of-day (EOD) treatments can also be an effective tool to regulate plant growth. Decoteau and Friend (1991) showed that red light given as EOD treatment to tomato significantly reduced plant height, while Hatt Graham and Decoteau (1995) showed that white fluorescent light given for 1 hour at the end of the photoperiod reduced plant height in bell pepper transplants. A more recent study found that monochromatic far-red light, given for only 15 minutes directly after the photoperiod, increases the internodal length of watermelon transplants (Damayanthi Ranwala and Decoteau 2007).

In ornamental plant production it is often the aim to inhibit the growth of plants in order to obtain a product that is compact and rich in shoots and flowers (Löfkvist 2010). Chemical growth retardants such as Flurprimidol, Cycocel and Paclobutrazol are often used to achieve the desired plant quality. However, the availability to these

substances is limited in many European countries due to national and EU regulations, and a reduction in the use of growth retardants is generally requested (Hendriks and Ueber 1995; Lökke and Christensen 2008; Löfkvist 2010). The use of light for regulation of plant morphology and development is thus relevant (Folta and Childers 2008; van Ieperen 2012), although active modulation of light quality to regulate plant growth has so far not reached widespread commercial use.

Many previous studies within this field only comprise short experiments performed in vitro, with little validity for commercial applications (Hirai et al. 2006). The objective of the present study was thus to evaluate the usefulness of narrow-band lighting provided by LED light for regulation of growth and flowering of ornamental pot plants during the full production cycle and growth of tomato transplants, and the effects on the photosynthetic capacity of plants. The aims of the experiments were to evaluate the use of narrow-band light as for controlling growth and flowering, and to investigate the phenomenon of plants acclimatising to narrow-band light. Our starting hypotheses were: i) Narrow-band light of certain spectra supplied as day extension efficiently inhibits flowering in short-day plants; ii) narrow-band light given as day extension affects the morphogenesis of plants; and iii) leaf photosynthetic capacity adapts to the quality of the light provided.

Materials and Methods

Two different experiments were carried out; a growth chamber experiment with LED light as the sole light source and a greenhouse experiment in natural daylight with LED as an end-of-day (EOD) treatment.

Growth chamber experiment with LED as light source

Two species of ornamental plants (*Pelargonium* × *hortorum* 'Americana Light Pink Splash' and *Helianthus annuus* 'Teddy Bear') were cultivated in 13-cm pots with Hasselfors K-soil (Hasselfors Garden, Örebro, Sweden) and kept in a growth chamber for 7 (*Pelargonium*) or 10 (*Helianthus*) weeks (set-point temperature 20 °C) with no influx of natural light. LED devices (90 W, TRG Components, Arboga, Sweden) were used as the sole light source. Five light qualities were tested: Blue (λ 460 nm), green (λ 535 nm), red (λ 660 nm), yellow (λ 580 nm), polychromatic white (λ 430–730 nm) and red/blue (λ 460/660 nm), at a ratio of 8:1 (only *Helianthus* experiment), all at a PPFD of 60 μmol m^{-2} s^{-1}. The photoperiod was 18 h day^{-1}. The chamber was divided into five smaller compartments for each treatments using reflecting plastic foil. Plants were irrigated with respect to water depletion and nutrient solution (alternately Superba NPK 14–4–21 + micronutrients and $Ca(NO_3)_2$, EC 2.0; Yara AB, Oslo, Norway) was supplied twice weekly (50 mL per pot). There were five plants per treatment. The experiments were conducted twice consecutively.

EOD experiment

The EOD experiment was performed in a 50 m^2 experimental greenhouse at Alnarp, Sweden (55 ° N, 13 ° E). The greenhouse was a wide-span greenhouse with covering material Plexiglas® SDP 16/980 (Röhm, Darmstadt, Germany). Three different plant species were used: *Solanum lycopersicum* 'Aromata', *Petunia* × *grandiflora* 'Raspberry Blast', and *Pelargonium* × *hortorum* 'Americana Light Pink Splash'. The plants were grown in a greenhouse chamber at 18 °C heating temperature, with vents opening when temperature exceeded set-points by 2 °C. End-of-day treatment with LED was given for 8 h after an 8-h period of natural light, and was followed by 8 h of darkness. During EOD treatment and darkness, light was excluded by screens (ILS Hortiroll, Ludvig Svensson, Kinna, Sweden). Five LED treatments were used: Blue (λ 460 nm), green (λ 525 nm), red (λ 620 nm), yellow (λ 585 nm) and polychromatic white (λ 430–730 nm). The light source was 22 W LED devices (TRG Components, Arboga, Sweden). The different treatments were separated using reflecting sheets. The LED light was supplied at an intensity of 20 μmol m^{-2} s^{-1}, measured at the top of the canopy. Plants were grown for a period of six (*Solanum*) or seven (*Pelargonium*, *Petunia*) weeks in the period February–May. Plants were irrigated with respect to water depletion and nutrient solution (Superba 14–4–21 + micronutrients and $Ca(NO_3)_2$, EC 2.5; Yara AB, Oslo, Norway) was given weekly. There were seven plants per treatment and the experiments were repeated twice in two consecutive years.

Biometric measurements

In the EOD experiment, the length of the apical main shoot was recorded weekly during the culture period. At the end of the experiment, plant height, width, internodal length, number of lateral shoots, number of buds/flowers and fresh/dry weight were recorded.

In the growth chamber experiment, the length of the longest shoot was recorded weekly. Plant height, width, stem diameter, bud/flower development, fresh weight, dry weight and internodal length were measured at the end of the experiment.

Photosynthesis measurements

Photosynthetic rate (A) and stomatal conductance (g_s) were measured (LCpro+, ADC BioScientific Ltd, UK) both in ambient light conditions (*Pelargonium*, greenhouse), at standardized (1500 μmol m^{-2} s^{-1}, *Pelargonium*, climate chamber) and at different (*Helianthus*) PPFD levels (0–1800 μmol m^{-2} s^{-1}) using the machine's built-in LED array (in the EOD experiments measurements were made

in natural daylight conditions). The measurements were performed at ambient CO_2 levels and at 20 °C. The third fully developed leaf, counted from the apex, was used for the measurements. The values were plotted and curves were fitted to the model y = c*(1-exp(−b*(intensity + a))) by non-linear regression in Minitab (Minitab version 16.1).

Physical analysis

The light intensity was measured at the top of the canopy at the beginning and end of the experiments (Delta OHM HD 2302.0, probe LP 471, Delta OHM, Padua, Italy). The spectral distribution of the light sources was measured at the beginning of the experiment using a spectroradiometer (Licor LI-1800, LI-COR, Lincoln, USA). The air temperature (°C) and humidity (RH, %) at canopy level were logged every 30 minutes by a data logger (HOBO U12, Onset Computer Corp., Bourne, USA) (EOD experiments). For the growth chamber experiment, the temperature in the growth chamber was logged every 30 minutes (HOBO H8, Onset Computer Corp., Bourne, USA).

Statistical analysis

The experiments were repeated in two consecutive years, with 9 replicate plants during each year. In the growth chamber experiment, 3 (*Pelargonium*) or 9 (*Helianthus*) replicate plants were used. Data were subjected to ANOVA with Tukey's multiple comparison test, with $P < 0.05$ considered significant (Minitab 16, Minitab Inc., State College PA U.S.A.).

Results

Growth chamber experiments

The photosynthetic rate (A) was highest in blue light for *Pelargonium* with ambient light conditions in the growth chamber (Fig. 1). For stomatal conductance (g_s), no differences were found between treatments (data not shown). When plants were supplied with constant light at 1500 µmol m^{-2} s^{-1}, the photosynthetic rate was highest for plants grown in blue light, lowest for plants grown in green light and intermediate for plants grown in red, yellow or white light. For *Helianthus*, multi-point measurements of photosynthetic capacity revealed that plants precultivated in different light qualities responded with significantly different photosynthetic capacity to the red/blue light used in the measurement, with the lowest photosynthesis capacity for plants grown in red light (Fig. 2).

Plant development was strongly dependent on treatment. For *Pelargonium*, the number of lateral shoots and flower buds and the fresh weight were higher in plants grown in red light, compared with all other treatments. Flower stalks emerged only in plants grown in white, red or blue light. For *Helianthus*, plants grown in blue light were strongly elongated and had the longest internodes (Table 1). Fresh weight was highest for plants grown in red or red/ blue light. Visually, root development was by far most vigorous in plants grown in red light.

Mean air temperature in the growth chamber was 21.5 °C during the *Pelargonium* experiment and 20.7 °C during the *Helianthus* experiment (data not shown).

EOD experiments

In general, plants responded strongly to the different light qualities when applied as an 8-h prolongation of the photoperiod. There was a clear increment in shoot and internodal length with blue light for *Petunia* and *Pelargonium* in the EOD experiments, as in the growth chamber experiments (Table 2). Weekly measurements of shoot length showed that *Pelargonium* plants treated with blue light had significantly longer shoots four weeks after the start of treatment (Fig. 3). For *Petunia* the internodal length was greatest for plants grown in white and blue

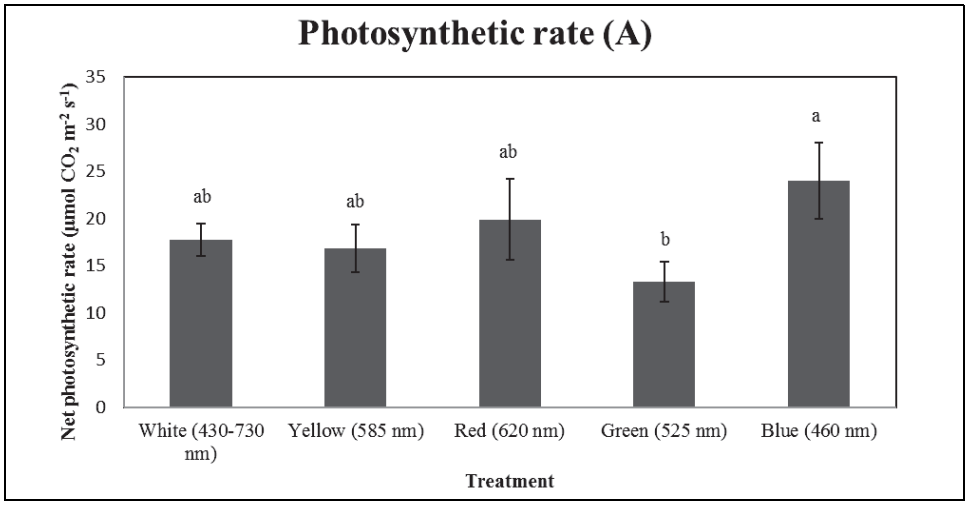


Fig. 1. Net photosynthesis (A) as a function of light quality in *Pelargonium* grown in five different light qualities in a growth chamber at PPFD 60 µmol m^{-2} s^{-1}. Photosynthesis was measured at 1500 µmol m^{-2} s^{-1}. Vertical bars represent standard errors. Bars that do not share a letter are statistically separated (Tukey's multiple comparison test, $P < 0.05$). N = 5.

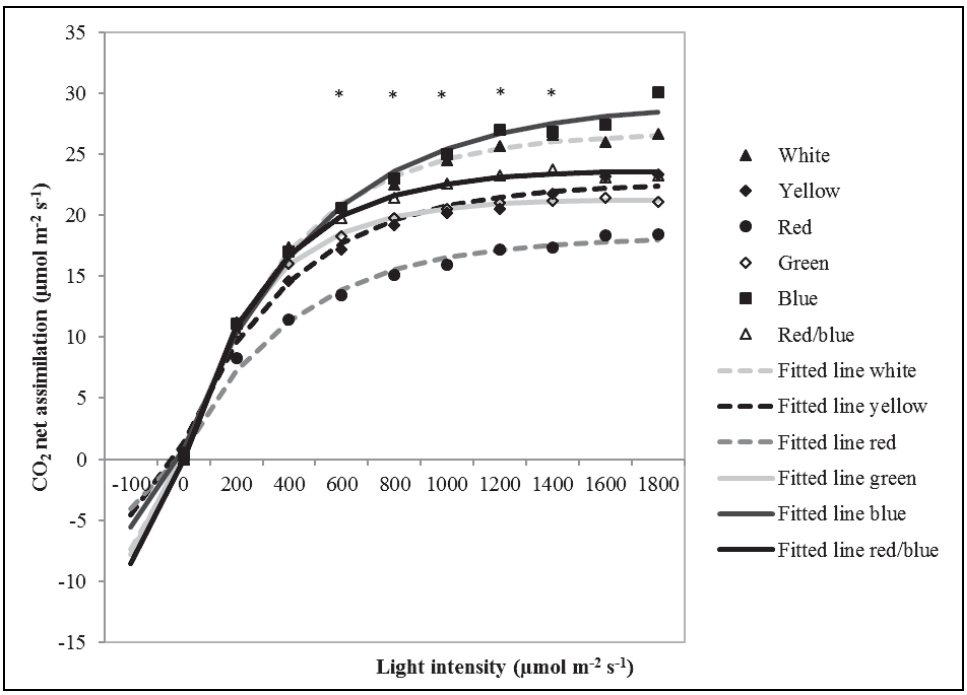


Fig. 2. Photosynthesis of *Helianthus annuus* measured using red/blue LED light at 10 different light intensities. Prior to measurements, the plants were grown for 4 weeks in six different light qualities. The curves were fitted using the model: y = c *(1–exp(–b *(intensity + a))). Asterisk (*) denotes significant difference (ANOVA, P < 0.05). N = 5.

Table 1. Plant development parameters in growth chamber experiments. Figures within rows marked with different letters are significantly different (P < 0.05). N = 6

Plant type	Parameter	White (430–730 nm)	Yellow (580 nm)	Red (660 nm)	Green (530 nm)	Blue (460 nm)	Red/blue (460/660 nm)
Pelargonium	Internodal length	10.4 a	4.3 a	6.3 a	4.3 a	7.4 a	
	Fresh weight	34.1 ab	23.6 c	42.1 a	24.1 bc	35.9 a	
	Dry weight	2.1 a	1.2 a	2.5 a	1.1 a	2.3 a	
Helianthus	Internodal length	11.8 b	10.9 b	11.7 b	10.6 b	24.0 a	11.2 b
	Fresh weight	59.6 b	61.9 b	85.9 a	59.0 b	62.7 b	81.7 a
	Dry weight	5.8 bc	5.2 c	11.0 a	4.7 c	7.2 b	11.4 a

light, while for *Pelargonium* it was greatest with blue light. For *Solanum*, however, internodal length was greatest in red light (Table 2). Stem diameter was smallest for *Petunia* grown in yellow light. Dry matter production was affected only in *Solanum* (Table 2). *Petunia* developed richness in flowering only when treated with white or blue light. In the treatment with yellow light, no flowers at all were present after the six-week cultivation period, while very few flowers were present on the plants that received red light as EOD treatment. In one of the replicate treatments the number of flower stalks produced was lower in *Petunia* treated with green light (data not shown). In the EOD treatments there were no differences with respect to photosynthetic rate or stomatal conductance (data not shown). There were no differences between treatments with respect to temperature and humidity (data not shown).

Discussion

This study examined the importance of narrow-band LED lighting in plant production ecology. The increase in stem elongation when plants were grown in blue light is contradictory to some previous findings (Evans et al. 1965; Mortensen and Strömme 1987; Appelgren 1991; Shimizu et al. 2005, 2006). One major difference in our study compared with other studies is the use of LED technology instead of spectral filters. It is possible that spectral filters allow pollution by spectral bands other than the intended (Parker et al. 1946), whereas the LED technology emits a sharp peak at the intended wavelength. Such light pollution has been reported for fluorescent tubes with spectral filters (Appelgren 1991). Alteration of red:far red ratio by spectral filters was also suggested by Mortensen and Strömme (1987). When using narrow-band LED light

Table 2. Plant development parameters in EOD experiments. Figures within rows marked with different letters are significantly different ($P < 0.05$). N = 18

Plant type	Parameter	White (430–730 nm)	Yellow (580 nm)	Red (620 nm)	Green (530 nm)	Blue (460 nm)
Solanum	Internodal length (mm)	44.0 ab	42.6 ab	47.6 a	38.1 b	47.2 a
	Stem diameter (mm)	8.0 a	8.0 a	7.8 a	8.1 a	7.8 a
	Fresh weight (g)	43.6 a	51.0 a	50.6 a	44.2 a	51.1 a
	Dry weight (g)	1.9 b	2.8 a	2.8 a	2.2 ab	2.6 a
Petunia	Internodal length (mm)	19.7 a	13.9 bc	13.5 c	17.4 ab	18.2 a
	Stem diameter (mm)	3.9 a	3.4 b	3.6 ab	3.7 ab	3.8 a
	Fresh weight (g)	52.2 ab	48.9 b	52.0 ab	56.1 a	56.8 a
	Dry weight (g)	4.0 a	3.2 a	3.3 a	4.0 a	4.0 a
Pelargonium	Internodal length (mm)	8.2 b	7.2 b	7.0 b	7.1 b	9.9 a
	Stem diameter (mm)	7.0 a	7.6 a	6.9 a	7.4 a	7.4 a
	Fresh weight (g)	61.6 a	62.9 a	57.1 a	53.3 a	66.8 a
	Dry weight (g)	4.8 a	5.3 a	4.8 a	4.3 a	5.6 a

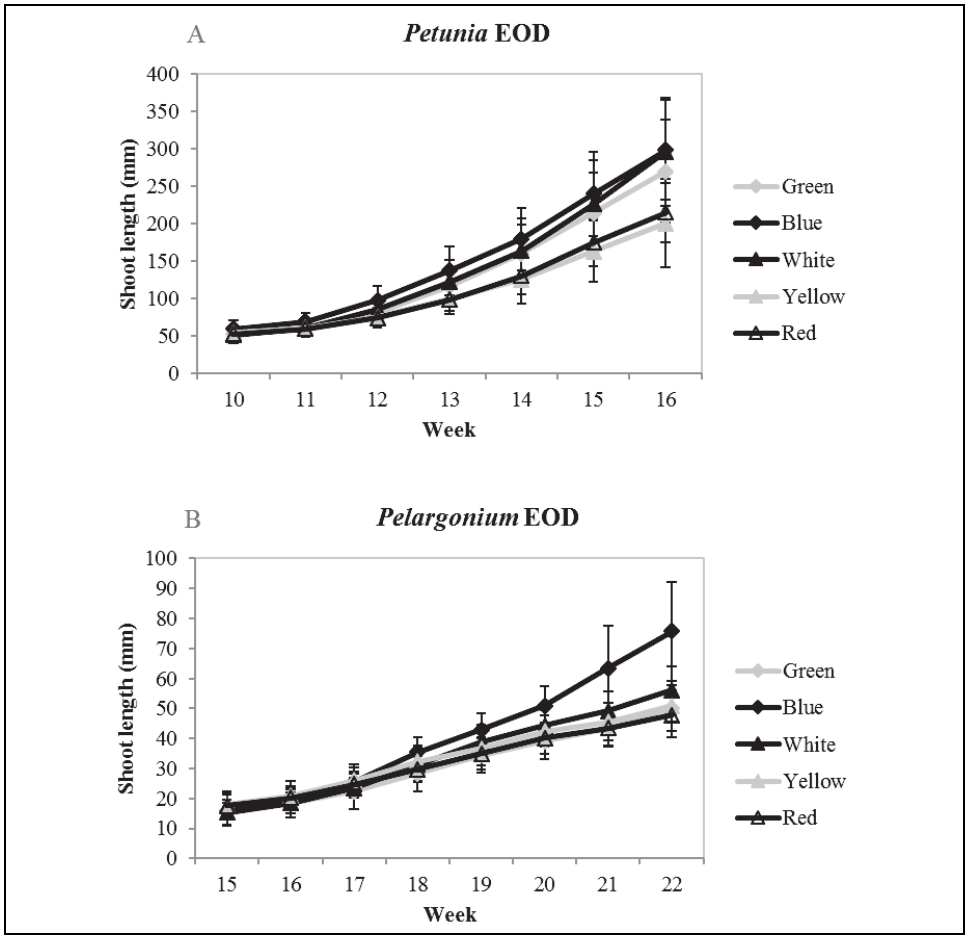


Fig. 3. Cumulative growth of the main shoot in *Petunia* (A) and *Pelargonium* (B), subjected to an 8-hour end-of-day treatment with narrow-band LED light of five different qualities (Green 525, Blue 460, White 430–730, Yellow 585 and Red 620 nm) at a PPFD of 20 µmol m^{-2} s^{-1}. N = 14.

sources emitting blue light, normally no red or far red light at all is emitted, so calculation of red:far red ratio is impossible in this case.

Results somewhat similar to ours with respect to plant development in blue light have been reported previously. For example, Hirai et al. (2006) observed increased stem

elongation in eggplant grown under blue LED and also presented data showing increased plant height in lettuce when grown under blue LED compared with green, red or blue + green LED. Fukuda et al. (2002) showed that blue LED light increased internodal length in *Petunia* in comparison with high pressure sodium lamps. Fukuda et al. (2011) demonstrated strong elongation in *Petunia* grown under blue LED compared with red LED or fluorescent tubes and also mentioned stimulation of the FBP28 gene by blue light as a probable cause of this elongation.

In previous studies, we demonstrated that *Chrysanthemum* plants given long-day treatment with blue LED initiated flowers when the light level was < 10 μmol m^{-2} s^{-1} (Bergstrand and Schüssler 2011). Blacquière et al. (1992) and de Graaf-van der Zande and Blacquière (1992) also found blue light to be less effective for floral regulation. Thus, the results on flower development for *Petunia* in the present study were rather surprising. Long-day treatments generally favour flower development in *Petunia* (Rünger 1965), but long-day treatment with yellow, green or red light at 30 μmol m^{-2} s^{-1} was obviously not enough to initiate flowers in this long-day plant. This is in sharp contrast to previous claims that the red and yellow parts of the spectrum are equivalent to daylight in the context of plant photoperiodic response, whereas green or blue light is perceived by the plants as darkness (Razumov 1933). The discrepancy between our results and older findings is probably due to the high purity of the LED light used in the present study compared with spectral filters. However, the absence of flowering when *Petunia* was grown in red light confirms findings by Fukuda et al. (2011) and can be explained by lack of signal from the cryptochrome.

The higher photosynthetic rate in *Petunia* for red light compared with blue light is surprising, as most studies have demonstrated lower photosynthetic levels in red light (Goins et al. 1997; Matsuda et al. 2004), as was also demonstrated in the present study for *Pelargonium*. The results in this study also differ from findings presented by Hogewoning et al. (2010), as red light was found to give higher photosynthetic yield than blue light in *Petunia*, but not in *Pelargonium*. This indicates that photosynthetic response is strongly dependent on plant species.

Acclimatisation of leaves with respect to light quality is a well-known phenomenon. The adaptations can constitute either long-term (thickness of epidermis, size of leaf, amount/type of chlorophyll) or short-term changes (stomata opening, orientation of chloroplasts). Long-term changes were reported by Walz and Horn (1997) with respect to quality of the artificial light used for *Chrysanthemum* and by Chabot et al. (1979) and Kasperbauer (1988) for *Fragaria*. Changes in photosynthetic capacity with respect to the direction of light given were demonstrated by Paradiso and Marcelis (2012). The lower long-term photosynthetic capacity of *Helianthus* leaves grown under red light in our study is not surprising, as red light is generally considered to be the most effective for plant photosynthetic systems, thus leading to less incentive for the plant to optimise the photosynthetic apparatus when red light is provided. However, the acclimatisation effect of leaves might partly explain the sometimes disappointing results from applying 'optimised spectra' to plants (Bergstrand and Schüssler 2012, 2013) and needs to be given attention when choosing a light source for horticultural applications. Our starting hypotheses (i–iii) were thus confirmed, with the exception that blue light was less effective in inhibiting flowering in short-day plants.

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