Budding and Bolting Responses of Horticultural Plants to Night-break Treatments with LEDs of Various Colors

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Abstract

We investigated the use of light-emitting diodes (LEDs) of particular wavelength emissions as light sources for night-break treatment of plants. We used the long-day plants godetia (*Godetia cvs.*), petunia (*Petunia × hybrida* Vilm.), and spinach (*Spinacia oleracea* L., two cultivars); and the short-day plants perilla (*Perilla ocymoides* L.), cosmos (*Cosmos bipinnatus* Cav.), yellow cosmos (*Cosmos sulphureus* Cav.), zinnia (*Zinnia elegans* Jacq.), and Japanese morning glory (*Pharbitis nil* Choisy). The plants were exposed daily to LED irradiation from 2300 to 0100 h during the short-day season (late autumn to early spring). Red and orange LED lights were effective in controlling flowering in all plants used in this study. Yellow and green LEDs were almost as effective. Far-red LED was effective in some, but not all, cases. One spinach cultivar bolted in response to far-red night-break treatment, but the other cultivar did not. Blue LED was effective in only one trial with perilla, but not so effective in other cases.

Key words: Flowering control, Light-emitting diode, Long-day plant, Midnight irradiation, Short-day plant.

1. Introduction

Light-emitting diodes (LEDs) have been investigated as the main light sources for indoor plant culture systems (Rula *et al.*, 1991; Brown *et al.*, 1995; Schuerger *et al.*, 1997), and as supplemental light sources for night-break treatments (Kawai *et al.*, 1996; Watanabe *et al.*, 1996). LEDs last longer than incandescent lamps, which are commonly used for night-break treatments. Kawai *et al.* (1996) and Watanabe *et al.* (1996) used red LEDs for night-break regulation of flowering in chrysanthemums

(*Dendranthema × grandiflorum*).

LEDs also have the characteristics of narrow spectral bandwidth emissions and small size (Schuerger *et al.*, 1997). Their narrow-band emissions make them useful for studies of the effects of light quality on plant physiology and growth. Until the early 1990s there were no LEDs available that emitted bright blue light, but this problem was solved by the introduction of gallium nitride as a material (Nakamura *et al.*, 1994). It is now possible to investigate the effects of light wavelength on flowering by using LEDs of many colors.

We investigated the use of LEDs emitting certain wavelengths as night-break light sources, and attempted to determine the most effective wavelength for the control of flowering in a number of long-day and short-day plant species.

2. Materials and Methods

2.1 Plants and light sources

We studied three species of long-day plants—godetia (*Godetia* ‘Satin Deep Rose’; *Oenotheraceae*),

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petunia (*Petunia* × *hybrida* Vilm. 'Baccara Red'; Solanaceae), and spinach (*Spinacia oleracea* L. 'Alrite' and 'Summer Focus'; Chenopodiaceae)—and five species of short-day plants—perilla (*Perilla ocymoides* L. 'Aochirimensis'; Lamiaceae), cosmos (*Cosmos bipinnatus* Cav. 'Radiance Special'; Asteraceae), yellow cosmos (*Cosmos sulphureus* Cav. 'Diablo'), zinnia (*Zinnia elegans* Jacq. 'Peter Pan Golden'; Asteraceae), and Japanese morning glory (*Pharbitis nil* Choisy 'Sunsmile Violet'; Convolvulaceae).

All of the plants, except for the yellow cosmos, were planted in 780-ml plastic pots (one plant per pot) filled with fertilized soil (N 0.4, P 0.7, K 0.3 g l⁻¹ soil). The yellow cosmos plants were planted in 90-ml pots in the same soil. Four plants of each species (three of perilla) were used for each treatment. The four pots were placed in a steel frame 600 mm wide × 400 mm long × 730 mm high with a ceiling; the frame and ceiling made shadows but they were not serious for plant growth. Six such frames were placed in a greenhouse to carry out a control with no night-break and five night-break treatments at a time. The greenhouse was heated when the temperature fell below 13°C and ventilated when the temperature rose above 30°C. Light was provided by six LED panels, each 350 × 400 mm, with peak photon emissions of 475 (blue), 530 (green), 576 (yellow), 594 (orange), 655 (red), or 745 (far-red) nm (Fig. 1). Each LED panel consisted of 800 individual LEDs. The frame containing control plants had no panels. For each night-break treatment, one LED panel of one color was mounted on the ceiling of a steel frame. Before the experiment,

the photon flux density from each LED panel was measured with a spectroradiometer (LI-1800, Li-Cor Inc., Lincoln, NE, USA). An electrical controller kept the photon flux density at floor level below the center of each LED panel between 8 and 10 $\mu\text{mol m}^{-2} \text{s}^{-1}$. The sides and back of each frame were covered with shade cloth from 1700 to 0900 h daily during each trial so that the plants could not be illuminated by LEDs of other colors. The LEDs irradiated the plants from 2300 to 0100 h daily during each trial.

2.2 Trial 1

Night-break treatments with blue, yellow, orange, red, or far-red LEDs were carried out from 23 November 1999. We used three species of young plants: perilla of 4 to 6 cm height and with four to six leaves, 'Alrite' spinach of 9 to 12 cm length with five or six leaves, and cosmos of 5 to 6 cm height and with two leaves. The short-day plants perilla and cosmos were given long-day treatment with irradiation (about 1 $\mu\text{mol m}^{-2} \text{s}^{-1}$) from an incandescent lamp from 1700 to 2100 h daily from germination until the beginning of the night-break treatments. This was done to avoid flower bud differentiation in the short-day plants before treatment began.

2.3 Trial 2

Two species were used, both long-day plants: godetia and 'Summer Focus' spinach, both of 2 cm height and with one leaf. Night-break treatments with blue, yellow, orange, red, and far-red light were started on 26 January 2000.

2.4 Trial 3

Three species were used: 'Alrite' spinach of 4 to 6 cm length and with two leaves, cosmos of 7 to 9 cm height and with four leaves, and perilla of 1 to 2 cm height and with a pair of cotyledons. The cosmos and perilla were illuminated with an incandescent lamp from germination until the beginning of the night-break treatments, as in trial 1. Night-break treatments with blue, green, yellow, red, or far-red light were begun on 9 November 2000.

2.5 Trial 4

Five species were used: zinnia of 3 to 4 cm height and with two leaves, Japanese morning glory of 1 to 2 cm height and with a pair of cotyledons, petunia less than 1 cm high and with six or seven leaves, godetia of 2 to 3 cm height and with four leaves, and yellow cosmos of 4 cm height and with two leaves. The zinnia, Japanese morning glory, and yellow

Fig. 1. Spectral distributions of LEDs used in this study. Relative photon flux of LEDs used in this study with peak=100% respectively.

cosmos were illuminated with an incandescent lamp until night-break treatment, in the same way as perilla and cosmos in trials 1 and 3. The night-breaks, with blue, green, yellow, red, or far-red LEDs, were started on 22 December 2000 for zinnia, 29 December for Japanese morning glory, 10 January 2001 for petunia, 24 January for godetia, and 26 January for yellow cosmos.

3. Results

3.1 Trial 1

Perilla flower stalks appeared on plants under blue-light treatment from 2 December (day 9 of treatment), when they had 10 to 12 leaves, on con-

trol plants kept in the dark at night (no night-break) from 6 December (day 13), when they had 11 to 13 leaves, and under both far-red and yellow-light treatments from 8 December (day 15), when the plants had 13 to 15 leaves. On 21 December (day 28, Fig. 2a), there were flower stalks on all plants under the control and far-red treatments, on two plants under the blue and yellow treatments, and on no plants under the orange and red treatments. Plants under either orange or red treatment had 14 or 15 leaves on day 28.

In this study, we define bolting spinach as spinach found elongation of flower stalk. The first spinach bolting (i.e. visible elongation of flower stalk) was found under the red, far-red, and yellow treatments on 11 December (day 18 of treatment), when the plants under these treatments had about 20 leaves. After that day, plants night-broken with orange light also had flower stalks (with 22 leaves). All plants except those under the control and blue treatments had bolted by 21 December (day 28, Fig. 2b). Plants under the control and blue treatments still did not have flower stalks at the 20-leaf stage.

In cosmos, the first flower bud appeared in controls on 24 December (day 31 of treatment), when the plants had 14 or 15 leaves. Night-break treatments with all colors inhibited the appearance of flower buds, but the effect of blue light was weaker than that of the other lights. Two plants night-broken with blue light were in anthesis or bud on 6 January (day 44, Fig. 2c).

3.2 Trial 2

Godetia flower buds appeared fastest under the red-light treatment, on 3 March (day 37 of treatment), when plants had 24 or 25 leaves, followed by the yellow- and orange-light treatments on 6 March (day 40), when the plants had between 26 and 28 leaves. Plants under control, blue, or far-red treatment had no buds on 13 March (day 47), the last day for counting of bud numbers, when the plants had about 30 leaves (Fig. 3a). After day 47, we kept two godetia plants for each treatment. Buds then appeared on 27 March (day 61) on plants under blue and far-red treatments, but the control plants still had no buds. Flower buds appeared on control plants on 3 April, one week later than on the blue- or far-red-treated plants.

Spinach flower stalks were found on 22 February (day 27 of treatment) in plants under red, yellow, or

Fig. 2. Number of flower stalks (dotted bars) and stalk length (solid circles) in (a) perilla and (b) spinach, and number of buds (striped bars) and flowers (solid bars) in cosmos (c) in trial 1. Data were collected on the last days for counting of flower stalks or buds and flowers: 21 December 1999 for perilla and spinach, and 6 January 2000 for cosmos. Numbers under the abscissa are individual numbers of plants under each treatment.

Fig. 3. Number of flower buds (striped bars) in godetia (a) and number of flower stalks (dotted bars) and stalk length (solid circles) in spinach (b) in trial 2. Data were collected on the last days for counting of flower stalks or buds: 13 March 2000 for godetia and 6 March 2000 for spinach. Numbers under the abscissa are individual numbers of plants under each treatment.

orange light; these plants had 10 to 14 leaves. On 6 March (day 40), there was no distinct bolting in the control, blue-, and far-red-treated plants, which had 12 to 17 leaves; the flower stalks of all of the plants under the other treatments had reached lengths between 19 and 38 cm (Fig. 3b).

3.3 Trial 3

Spinach plants under green, yellow, red, and far-red light bolted in late November, when they had 8 to 12 leaves. One plant under blue-light treatment bolted about 10 days later, when it had 13 leaves, but the other plants under blue light and all of the control plants had no visible flower stalks by 19 December (day 40 of treatment, Fig. 4a). The plants without flower stalks had reached the 13- to 19-leaf stage by 19 December.

Cosmos flower buds appeared in the controls in late November, at the 8- to 12-leaf stage. Ten days later, one plant under far-red treatment was in bud. On 27 December (day 48 of treatment), half of the

Fig. 4. Number of flower stalks (dotted bars) and stalk length (solid circles) in spinach (a); number of buds (striped bars) and flowers (solid bars) in cosmos (b); and number of flower stalks (dotted bars) in perilla (c) in trial 3. Data were collected on the last days for counting of flower stalks or buds and flowers: 19 December 2000 for spinach, 27 December 2000 for cosmos, and 4 January 2001 for perilla. Numbers under the abscissa are individual numbers of plants under each treatment.

plants under far-red light (at the 14- and 15-leaf stage) and under blue light (at the 19- and 21-leaf stage) had buds, and no flowers or buds were found on plants (which were at the 16- to 20-leaf stage) under the other light treatments; all of the control plants had reached anthesis (Fig. 4b).

In perilla, the first flower stalks appeared on the control plants on 19 December (day 40 of treatment), when the plants had 8 to 10 leaves. All of the night-break treatments inhibited the appearance of flower stalks (Fig. 4c). On 4 January (day 56, the day on which all of the plants subjected to night-break treatment had more than 10 leaves), there were still no flower stalks on any of the night-break-treated plants.

3.4 Trial 4

Terminal flower buds appeared on all zinnia plants in late January. However, lateral flower development was faster in control plants and in those treated with blue light than in the other groups. On 1 March (day 69 of treatment), open lateral flowers were apparent in only the controls and the blue-light-treated plants (Fig. 5a).

Control Japanese morning glory plants were fastest to bud, followed by blue-light-treated plants. The first flower bud was found in control plants with six leaves on 28 February (day 61 of treatment) and in blue-light-treated plants with eight leaves on 7 March (day 68). In the other treatments, flower buds appeared in mid March, when the plants had 10 or more leaves. On 20 March, there were plants in bud in all light groups (Fig. 5b).

Petunia flower development was fastest in red-

light-treated plants, and occurred at the 19- or 20-leaf stage. The highest occurrence of open flowers was in the red-light-treated plants on 12 March (day 61 of treatment, Fig. 5c). In the controls and far-red-treated plants, flower bud appearance and flower opening were later than in the other treatment groups.

In godetia, flower buds appeared in the red-, yellow-, and green-light treatment groups in late February, when the plants were at the 21- to 24-leaf stage. The first bud in the blue-treated plants was found on 13 March (day 48 of treatment, at the 35-leaf stage), a little faster than in the controls and the far-red-treated plants. By the time the control plants and those treated with far-red light developed flower buds, they had more than 40 leaves. On 23 March (day 58, the last day of the godetia experiments) there were fewer flower buds in the controls and the

Fig. 5. Number of terminal flowers (solid bars), lateral buds (striped bars), and lateral flowers (open bars) in zinnia (a) and number of buds (striped bars) and flowers (solid bars) in Japanese morning glory (b), petunia (c), godetia (d), and yellow cosmos (e) in trial 4. Data were collected on the last days for counting of buds and flowers: 1 March 2001 for zinnia, 20 March 2001 for Japanese morning glory, 12 March 2001 for petunia, 23 March 2001 for godetia, and 14 March 2001 for yellow cosmos. Numbers under the abscissa are individual numbers of plants under each treatment.

blue and far-red treatment groups than in the other groups (Fig. 5d).

Yellow cosmos buds appeared in the controls and in the blue- and far-red light groups in late February, when the plants had 8 to 10 leaves. By 14 March (day 47 of treatment, Fig. 5e), flower buds were also found in the green and yellow light groups (at the 12- to 15-leaf stage), but not in the red light group (which had 12 to 14 leaves). Some flowers were open in the control, blue, and far-red light groups on that day.

4. Discussion

Red and orange LED lights (wavelength range about 580 to 670 nm) would be effective in night-break treatment for the control of flowering in many long-day or short-day plants. In every one of our trials, flower induction was enhanced in long-day plants and inhibited in short-day plants by night-break treatment under lights of these colors. Yellow LED light (about 560 to 580 nm) would be almost as effective. Yellow light showed similar night-break effects to those of red or orange light, a little less in the cases of perilla in trial 1 and yellow cosmos in trial 4. Night-break with green LED light (about 500 to 560 nm) would be as effective as using yellow light, or a little less so, as can be seen from the results of trials 3 and 4. Far-red LED light (about 720 to 770 nm) would not be very useful for night-break treatment. Far-red was effective in some cases—with cosmos and 'Alrite' spinach in trial 1, with 'Alrite' spinach and perilla in trial 3, and with zinnia and Japanese morning glory in trial 4—but it was less effective in the other cases. Blue LED light (about 460 to 500 nm) would also not be a good choice for night-break treatment. It was the least effective of the lights we tested. Blue light had as strong a night-break effect as the other colors only in the case of perilla in trial 3. We cannot say that flower induction is not influenced at all by blue or far-red night-break light, but we can say that flower induction of a number of short-day and long-day plants is influenced to only a small extent by lights of these colors.

Nevertheless, from the evidence provided by following studies, night-break treatment with blue or far-red light appears to be strongly effective in long-day Brassicaceae. Moreover, green, yellow, orange, and red lights may not be effective in a number of

crucifers, because in Funke's study (Funke, 1948), blue light acted as "light" and red as darkness to many cruciferous plants. Also, Wassink *et al.* (1951) reported that flowering of turnip (*Brassica rapa*), a long-day cruciferous plant, was promoted by supplementation with blue light for the elongation of day length. Stolwijk (1952) reported that flowering of yellow mustard (*Sinapis alba*), another long-day crucifer, was promoted more by the elongation of day length with blue supplemental light than with green, yellow, or red light. Goto *et al.* (1991) reported that floral initiation of the long-day crucifer *Arabidopsis thaliana* was more enhanced by night-break treatment with blue light (with a peak of 460 nm) or far-red light (with a peak of 750 nm) than by night-break treatment with red light (with a peak of 655 nm). Brown and Klein (1971) performed a photoperiod elongation treatment on *Arabidopsis thaliana* with colored lights through filters that passed narrow-band wavelengths (central wavelength ± 5 nm). They reported that light with a central wavelength of 455, 500, 700, or 730 nm induced flowering, but light with a central wavelength of 550, 600, or 660 nm did not induce flowering.

In contrast, the results of many studies that have used plants other than crucifers agree with those of our study, which did not use crucifers. Elongation of day length with green, yellow, or red supplemental lights delayed flowering of cosmos (Wassink *et al.*, 1951) and promoted flowering in spinach (Stolwijk, 1952). Stolwijk (1952) reported that flowering of cosmos was delayed by night-break treatment with green, yellow, or red light. Negretsky (1993) reported that night-break treatment with a 554-nm laser beam delayed flowering of red goosefoot (*Chenopodium rubrum*), and treatment with 516-nm laser light delayed flowering of tobacco (*Nicotiana tabacum*). These are both short-day plants. Kawai *et al.* (1996) reported that flowering of chrysanthemum, a short-day plant, was delayed by night-break treatment with a red LED light with a 660-nm peak emission. Taking these studies into consideration, we can say with certainty that flower induction in many non-cruciferous short-day or long-day plants responds well to red, yellow, or green light, but poorly to blue or far-red light. It is known that green light (500- to 560-nm wavelength) is poorly absorbed by phytochrome photoreceptors, which play a role in flower induction in short-day and long-day plants

(Nagatani, 2001; Tokutomi, 2001). However, the results of this study showed that green light affected plant flowering. Therefore, other photoreceptors may also play a role in flower induction.

From the results of our trials 1, 2, and 3, it can be seen that the response of spinach to far-red night-break treatment probably differs by cultivar. 'Alrite' spinach was affected by the far-red night-break, but 'Summer Focus' was not. We also obtained similar results in other studies (Hamamoto *et al.*, 2000; 2002). These results suggest that the wavelength range strongly effective for flower induction may be wider in 'Alrite' than in 'Summer Focus'.

In the short-day plant perilla, the range of wavelength that effectively inhibited flower induction was wider in trial 3 than in trial 1, which started with the use of older plants (at the four- to six-leaf stage) than those used in trial 3 (at the cotyledon stage). Similarly, the range of wavelength that effectively inhibited flower induction of cosmos, another short-day plant, was wider in trial 1, which started with the use of two-leaf-stage plants, than in trial 3, which started with the use of four-leaf-stage plants. These two cases suggest that the effective wavelength range may be wider in young plants than in old plants. However, our results for godetia, a long-day plant, show that the acceleration of flower induction by yellow night-break treatment was slightly greater in trial 4 (beginning at the four-leaf stage) than in trial 2 (beginning at the one-leaf stage). The relationship between plant age and the effective wavelength range for the induction of flowering is worthy of further study.

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各色 LED による暗期中断処理に対する園芸植物の 出蕾と抽だい反応

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要 約

長日植物のゴデチア、ペチュニア、ハウレンソウ、短日植物のシソ、コスモス、キバナコスモス、ジニア、アサガオについて、青、緑、黄、橙、赤、遠赤色（それぞれピーク波長 475, 530, 576, 594, 655, 745 nm）の発光ダイオード（LED）による深夜 2 時間の暗期中断の出蕾や抽だいに対する効果を検討した。赤色および橙色の光は本試験で供試した長日植物の花成促進、短日植物の花成抑制にもっとも効果的であった。黄色、緑色光を用いた場合も赤、橙色光に近い効果が得られた。遠赤色光はハウレンソウの 1 品種において花成促進に働いたが、他の植物には安定した効果はみられなかった。青色光処理に

はシソにおいてのみ、花穂出現を抑制した場合があったが、その他の場合にはさほど効果がなかった。

キーワード: 花成制御、発光ダイオード、長日植物、深夜照明、短日植物

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