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Effect of end-of-day far-red light from a movable LED fixture on squash rootstock hypocotyl elongation

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ABSTRACT

Effects of end-of-day far-red (EOD-FR) light on hypocotyl elongation of a commercial cucurbit rootstock were investigated using movable and stationary light fixtures, since adequate hypocotyl length is required in vegetable grafting. Seedlings of an interspecific squash 'Tetsukabuto' (*Cucurbita maxima x Cucurbita moschata*) were grown in greenhouse and subject to daily EOD-FR light treatments with various application methods. The response of seedling hypocotyl length was well described using a Michaelis–Menten-type saturation curve over the range of 0–8.8 mmol m^{-2} d^{-1} FR light doses, as we previously reported for tomato rootstocks. Using a near saturating dose of 4.0 mmol m^{-2} d^{-1} FR light, efficacy of a movable FR light fixture for EOD-FR light treatment was compared with that of a stationary FR light fixture. The movable light fixture was a 120-cm metal bar equipped with FR light emitting diodes (LEDs) and the application was tested at two different traveling speeds (0.78 and 3.13 mm s^{-1}) with one and four repeated applications per day, respectively, to reach the same target FR light dose (4.0 mmol m^{-2} d^{-1}). Regardless of traveling speed, the extent of hypocotyl elongation under the moving FR LED fixture was statistically the same as that under stationary LED fixture and was 55–69% greater than non-treated control, suggesting that EOD-FR light applications can be designed flexibly. As far as we are aware, this is the first paper demonstrating the effect of EOD light quality treatment using moving light fixtures.

1. Introduction

Vegetable grafting as a means to achieve yield increase and pest/disease control has received increasing attention worldwide (Kubota et al., 2008; Colla, 2010), especially with the progressive limitation of fumigant use including methyl bromide. Seedling morphology control is a key technology in transplant production and various non-chemical approaches were studied, such as temperature control (Erwin et al., 1989) and light quality modification (e.g., Decoteau et al., 1988; Rajapakse et al., 1993). In vegetable grafting propagation, especially for rootstock, lengthening the hypocotyl is critical to increase the grafting speed as well as to prevent the vulnerable scion from coming in contact with the soil during and after transplanting (Chia and Kubota, 2010). Furthermore, cucurbit rootstock seedlings are often grafted without roots (grafted cuttings) to increase the grafting efficiency and then re-rooted during the healing process (Lee and Oda, 2003). This process requires rootstocks with long hypocotyls. A commercially acceptable target length of cucurbit rootstock hypocotyl for grafting is at least 7 cm (personal communication, Berg Earth Co., Japan). The authors are aware that commercial propagators combine various non-chemical techniques (shading, water management, and temperature control) to assure long hypocotyls of cucurbit rootstocks. Challenges are, however, to consistently produce rootstocks with long hypocotyls as the elongation rate can be influenced by seasonal changes in greenhouse environmental conditions. Furthermore, production of uniform rootstock and scion seedlings is especially important for mechanical grafting, which is considered as a future means to produce large numbers of grafted seedlings (Kubota et al., 2008).

End-of-day (EOD) light quality treatment has been studied as an effective method to control stem and hypocotyl elongation (e.g., Decoteau et al., 1988; Blom et al., 1995; Chia and Kubota, 2010). Due to the low light intensity requirement and recently increasing availability of light emitting diodes (LED), EOD light quality treatment may be an economically feasible non-chemical means to control plant morphology, in which EOD-red (R, 600–700 nm wavelength) and far-red (FR, 700–800 nm wavelength) light treatments can reduce and enhance the stem/hypocotyl elongation rate,

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respectively. The stem elongation altered by EOD light treatments is a phytochrome mediated plant response. Using two tomato rootstocks, Chia and Kubota (2010) showed the EOD-FR light dose response of hypocotyl elongation and demonstrated that both FR light intensity and duration could be flexibly selected to provide a saturation FR light dose (light intensity × duration). Therefore, small numbers of high-output FR LEDs combined with a horizontally traveling light fixture could achieve a saturation dose, compared with the traditional lighting design where large number of light fixtures are distributed horizontally over the greenhouse headspace.

Our present study consists of two parts: the first part was to quantify the EOD-FR light dose response of an interspecific squash rootstock widely used for cucumber and watermelon grafting. The second part was to demonstrate the efficacy of a movable light fixture for EOD-FR treatment.

2. Materials and methods

2.1. Plant materials and growth conditions

Interspecific squash rootstock 'Tetsukabuto' (*Cucurbita maxima x Cucurbita moschata*) (American Takii, Salinas, CA, USA) was used. Seeds were sown in 98-cell seedling trays (tray size: 28 cm × 55 cm; one seedling per cell) filled with commercial substrate (SunGro Sunshine Professional Mix 3, Bellevue, WA, USA) then covered with a thin layer of vermiculite. Seeded trays were kept in darkness for the first 2–3 days and the substrate temperature was maintained at 30 °C up to the 5th day after seeding. The greenhouses (Tucson, AZ, USA) were covered by inflated double-layered polyethylene film (dose response experiment) or a double-layered acrylic panel (movable lighting experiment), and equipped with pad-and-fan cooling and hot air heating systems using natural gas. When the cotyledons of seedlings were fully expanded, uniform seedlings were selected for the treatments. The plants were subirrigated daily throughout the treatment with nutrient solution (EC ∼ 1.0 dS m^{-1}) containing (in mg/L) 62 NO_3—N, 15 NH_4—N, 22 P, 112 K, 12 Mg, 62 Ca, 49 S and 13 Cl as well as micro nutrients.

2.2. Movable FR LED light source

A FR LED bar (ORBITEC, Co., Madison, WI, USA), 120 cm in length with 40 LEDs (peak wave length: 742 nm, half bandwidth: 31 nm), was mounted on the underside of the moveable carriage of a belt drive (ERV, Parker Hannifin Co., Rohnert Park, CA, USA) operated by a programmable motion controller (MDrive23, Schneider Electric Motion, Marlborough, CT, USA). The entire apparatus was supported by a metal platform (1500 mm (l) × 1200 mm (w) × 500 mm (h)) and covered by an opaque plastic film to prevent light contamination during the experiment. Before starting the experiment, intensities of FR light emitted from the LED bar were measured over the horizontal x–y plane 5 cm below the LED bar using a spectroradiometer (PAR-NIR, Apogee Instruments Inc., Logan, UT, USA) (Fig. 1). The FR light intensity (photon flux integrated for 700–800 nm) was the greatest just below the LED bar (24.8 ± 4.8 μmol m^{-2} s^{-1}) and decayed rapidly along the y-axis or the traveling direction of LED bar (Fig. 1). The FR light intensities were less than 0.1 μmol m^{-2} s^{-1} outside the 700 mm distance ($-350 \leq y \leq 350$; in mm) along the traveling direction (perpendicular to the LED bar longitudinal direction). The FR light intensities were more uniformly distributed along x-axis and its coefficient of variation was only 3% below the LED bar. Therefore, in the present experiment, the central 700 mm × 700 mm area was considered as the effective area that can receive measurable FR photon flux from the LED bar (average over the area: 4.48 μmol m^{-2} s^{-1}).

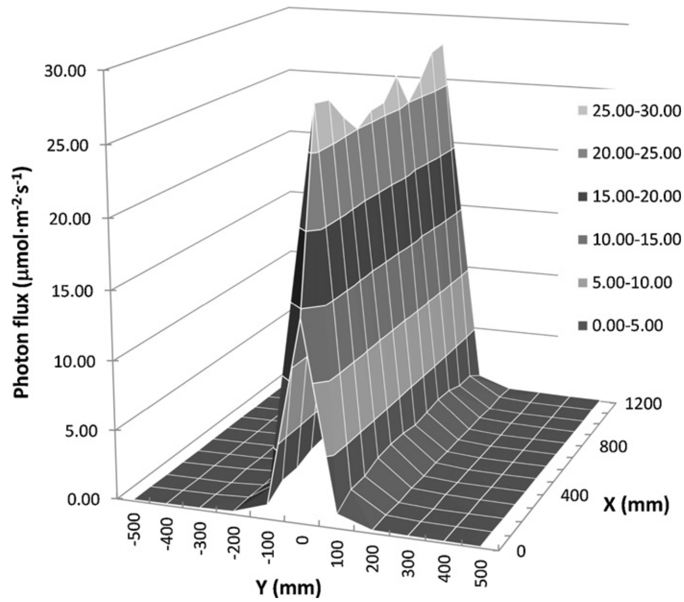

Fig. 1. Horizontal photon flux distribution measured under the far-red (FR) LED bar used in the present experiment (measurement plane was 5 cm below the LED bar). LED bar was designed to move along the y-axis when used as moving fixture for the end-of-day FR light treatment.

The traveling speed of FR LED bar was determined using the following equations. Under a steady traveling speed in the direction perpendicular to the LED bar, the FR light dose that the seedlings receive while the light fixture is passing above the canopy is expressed using a function of traveling speed and the total FR photon flux emitted from the fixture. In this experiment, the total photon flux emitted from the light fixture (LED bar) was approximated by the average FR light intensity over the effective area. Therefore, the time duration necessary to expose the seedlings to provide the selected dose of FR light can be determined by:

$$t = \frac{D_{FR}}{I_{FR}} \tag{1}$$

where t is the FR light exposure time (s) at intensities greater than 0.1 μmol m^{-2} s^{-1}; D_{FR} is the target FR light dose (μmol m^{-2}); and I_{FR} is the average FR light intensity (μmol m^{-2} s^{-1}) in the effective area (700 mm × 700 mm). More strictly, average FR light intensity should be computed in each of the narrow traveling corridors affecting the corresponding seedling row in the tray. However, in the present experiment, we used the area considering the relatively high uniformity of LED output between rows and the fact that we rotated seedling positions every day within the tray to ensure greater uniformity in plant response. The D_{FR} and I_{FR} in our experiment were 4.0 mmol m^{-2} (selected from the dose response experiment) and 4.48 μmol m^{-2} s^{-1}, respectively, giving the FR exposure time as 893 s. The LED bar's traveling speed (v, m s^{-1}) can be therefore computed as:

$$v = \frac{L}{t} \tag{2}$$

where L is the effective exposure length (m) longitudinal to the traveling path. In our present experiment, L was 700 mm (selected as the distance where the FR light intensity is greater than 0.1 μmol m^{-2} s^{-1}), giving the required traveling speed as 0.78 mm s^{-1}. When more than one application are intended, the effective exposure length is the multiplication of this distance and therefore the traveling speed needs to be proportionally increased to meet the same dose requirement.

Table 1
Red to far-red photon flux ratio (R/FR), phytochrome photostationary state (P_{fr}/P_{total}), far-red light intensity, dose, treatment light exposure time per day, traveling speed (v) and application times per day applied at the end-of-day (EOD) employed in the experiment comparing EOD FR treatment using movable vs. stationary LED fixture. Applications of EOD-FR from movable LED fixture were examined at two speeds (0.78 and 3.13 mm s^{-1}) with corresponding number of applications (once and four times per day) to achieve the same dose (4.0 mmol m^{-2} d^{-1}).

Treatment	R/FR	P_{fr}/P_{total} [a]	FR intensity[b] (μmol m^{-2} s^{-1})	FR dose (mmol m^{-2} d^{-1})	Exposure (s)	v[c] (mm s^{-1})	Application (d^{-1})
Movable LED-1	0.024	0.098	4.47	4.0	893	0.78	1
Movable LED-4	0.024	0.098	4.47	4.0	893	3.13	4
Stationary LED control	0.021	0.089	6.22	4.0	643	0	0

[a] Phytochrome photostationary state (Sager et al., 1988).
[b] Average of effective area for the treatment. Photon flux distribution of movable LED fixture is shown in Fig. 1.
[c] Two different traveling speeds of the LED bar were applied.

2.3. Stationary FR LED light source

The programmable LED lighting panel (339 mm × 350 mm; Model: ISL-RFGB, CCS Inc., Kyoto, Japan) with FR LEDs (peak wavelength: 734 nm, half bandwidth: 24 nm) was used for the stationary FR light source. The panel was placed horizontally inside an opaque cardboard box that prevented light contamination during the experiment.

2.4. EOD-FR light treatments

Table 1 shows the summary of light source, R/FR ratio, phytochrome photostationary state, FR light intensity, dosage, exposure time and traveling speed employed in the experiments. The height of LED bar was maintained at a distance of 5 cm above the plant canopy while the seedlings were subject to the FR light treatment. Due to the differences in light quality (i.e., peak wavelength) between the LEDs used for movable and stationary fixtures, we compared the light quality using the phytochrome photostationary state (P_{fr}/P_{total}) estimated according to Sager et al. (1988) in addition to a simple parameter R/FR photon flux ratio (Table 1). When different light sources are used to control phytochrome-mediated response, use of P_{fr}/P_{total} is more appropriate than simple R/FR ratio to compare the light qualities as it represents the relative amount of phytochrome in the active isoform (P_{fr}) compared to total phytochrome (P_{total}) in the plant. The small difference in P_{fr}/P_{total} for the LEDs used in the movable bar fixture (0.098) and the stationary LED light fixture (0.089) (Table 1) was considered negligible, based on the previous study reporting the responses of cucumber seedling to varied phytochrome photostationary state employed for EOD-FR light treatment (Gaba and Black, 1985).

After 5 days from seeding, seedlings were subject to daily EOD-FR light treatments. The EOD treatments were initiated at 6:30 PM every day inside two opaque chambers containing either the stationary or the movable LED fixture mentioned above. There was also one opaque chamber for the non-treated control. The FR light treatment chambers were loosely closed to allow natural ventilation so that there would be no significant difference in the temperature and gas (such as CO_2) environments inside and outside of the chambers, while optically isolating the chambers. The seedlings were kept inside the chambers during the night and taken out of the boxes at 7:00 AM of the following day. Air temperature within each treatment chamber was monitored using a thermocouple (Type T, 0.75 mm in diameter) and recorded at 10 min intervals using a CR-23X datalogger (Campbell Scientific, Logan, UT, USA). There was no significant difference between the treatments and control of the nighttime air temperature inside the chambers (data not shown). Control treatments did not receive any EOD-FR light treatment although the plants were still kept in the chamber without lights from 6:30 PM to 7:00 AM to prevent light contamination from external light sources.

For the EOD-FR light dose experiment, the experimental conditions were identical to the movable EOD-FR light fixture experiment except that there were four levels of EOD-FR dose varied with combinations of FR light intensity and exposure time (duration) following the methods described by Chia and Kubota (2010). Namely, the light intensity-duration treatments applied in this experiment were (1) 1.3 μmol m^{-2} s^{-1} for 12 min (0.9 mmol m^{-2} d^{-1} dose), (2) 1.5 μmol m^{-2} s^{-1} for 24 min (2.1 mmol m^{-2} d^{-1}), (3) 2.7 μmol m^{-2} s^{-1} for 12 min (1.9 mmol m^{-2} d^{-1}), (4) 2.4 μmol m^{-2} s^{-1} for 24 min (3.5 mmol m^{-2} d^{-1}), and finally (5) 44 μmol m^{-2} s^{-1} for 3.3 min (8.8 mmol m^{-2} d^{-1}). The second and third treatments were included to examine different combinations of FR light intensity and duration at a similar FR light dose (~2.0 mmol m^{-2} d^{-1}), following the design of Chia and Kubota (2010). The EOD-FR light treatments were applied for ten consecutive days. The light source for the highest FR dose 8.8 mmol m^{-2} d^{-1} was the same LED panel described above, while the light source for lower FR light doses (0.9, 1.9, 2.1, and 3.5 mmol m^{-2} d^{-1}) was a combination of a spectral filter and incandescent lamps as described in Chia and Kubota (2010).

Movable EOD-FR light treatment was examined at two different traveling speeds that provided the same EOD-FR light dose (4.0 mmol m^{-2} d^{-1}) (Table 1). One traveling speed was 0.78 mm s^{-1}, achieving the target FR dose by one application (one trip over the plant canopy). The other traveling speed was four-times faster (3.13 mm s^{-1}) with four applications (two round trips over the plant canopy), in which the light fixture turning point was selected at 350 mm beyond the end edge of plant canopy so that the light fixture would not start moving backward before the seedlings received the complete exposure of FR light emitted over the effective area beneath the LED bar (700 mm in length). The EOD-FR light treatments were applied every day for five consecutive days.

2.5. Plant measurements and experimental design

Hypocotyl length was measured daily using a ruler. Hypocotyl diameter, and aerial part fresh and dry weight of the seedlings were measured using a digital caliper and an electronic balance.

The EOD-FR light dose response experiment was conducted once (May 26, 2009 to June 10, 2009) with 24 seedlings per treatment (144 seedlings in total). During the experiment, mean daytime and nighttime average temperatures inside the greenhouse were recorded as 26.1 ± 0.65 and 19.8 ± 0.42 °C, respectively. The movable EOD-FR light experiment was repeated three times (replicated over time) each with nine seedlings per treatment (162 seedlings in total) ((1) 15–25 June, (2) 23 June–3 July, and (3) 28 June–8 July 2010 for slow traveling speed; (4) 3–13 July, (5) 8–18 July and (6) 13–23 July 2010 for fast traveling speed). Stationary EOD-FR and non-treated controls were included as reference in each replication. During these six experimental periods, mean daytime temperatures inside the greenhouse were recorded as 25.1 ± 0.49, 26.0 ± 0.62, 26.0 ± 0.77, 26.6 ± 1.16, 27.7 ± 0.77, and 27.5 ± 1.12 °C and nighttime temperatures were 19.3 ± 1.70, 21.1 ± 0.97, 21.3 ± 0.90, 22.3 ± 1.58, 24.0 ± 0.63, and 23.9 ± 0.77 °C, respectively. Similarly, daily light integral (in

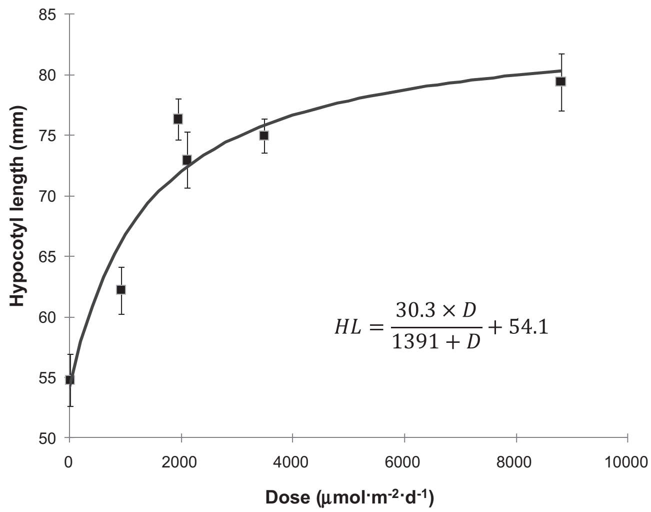

Fig. 2. End-of-day far-red (EOD-FR) light dose–responses of interspecific squash rootstock hypocotyl elongation after ten consecutive days of EOD-FR treatment. Data were fitted with a Michaelis–Menten-type model: $HL = (V_{max} \times D)/(K_M + D) + H_0$, where *HL*, represent hypocotyl length (millimeters); V_{max}, maximum increase in hypocotyl length at saturation dose (30.3 mm); *D*, FR light dose (μmol m^{-2} d^{-1}); K_M, Michaelis–Menten parameter (1391 μmol m^{-2} d^{-1}); and H_0, hypocotyl length of untreated control ($D = 0$) (54.1 mm). Means are shown with standard errors ($n = 24$).

mol m^{-2} d^{-1}) inside the greenhouse was 19.0 ± 0.74, 19.4 ± 0.35, 19.4 ± 0.34, 19.3 ± 0.37, 19.3 ± 0.31, and 18.9 ± 1.06, respectively.

Despite the differences in greenhouse microclimates between the replications, analysis of variance confirmed that there were no significant interactions between treatment and replication (time of experiment). The results were analyzed using JMP statistical software (SAS Institute, Cary, NC, USA).

3. Results and discussion

3.1. EOD-FR light dose response

'Tetsukabuto' interspecific squash hypocotyl lengths increased with increasing EOD-FR light dose in the range of 0–8.8 mmol m^{-2} d^{-1} (Fig. 2). The hypocotyls at the greatest dose were 44% longer than that for the non-treated control. The target FR light intensity of 4.0 mmol m^{-2} d^{-1} tested for the movable LED fixture was a near-saturation dose as shown in the response.

In EOD light quality treatments, plants respond to relatively short durations of either *R* or FR light at the end of the photoperiod, after which the dark period would continue as per normal (Fredericq, 1964). Enhanced stem elongation under EOD-FR light treatment were reported for various plant species including chrysanthemum (Rajapakse et al., 1993; Lund et al., 2007), lilies (Blom et al., 1995), watermelon (Hatt Graham and Decoteau, 1997), cowpea (Martinez-Garcia et al., 2000), cucumber (Xiong et al., 2002, 2011), and tomato (Chia and Kubota, 2010). Intensities and duration of EOD-FR treatments applied in these studies varied widely, and they were often selected to give a dose beyond saturation so that maximum response would occur (except Chia and Kubota, 2010). Therefore, understanding phytochrome kinetics (or dose–response) would help in selecting the necessary light intensity, quality, and treatment duration. To our knowledge, only a limited number of plant species relevant to greenhouse production, including *Cucumis sativus* (Gaba and Black, 1985), *Solanum lycopersicum*, and *S. lycopersicum x S. habrochaites* (Chia and Kubota, 2010), were well studied for kinetic response to EOD-FR light treatments. In the study conducted by Gaba and Black (1985), saturation responses to FR light dose similar to our finding on interspecific squash seedlings were observed for cucumber seedlings grown under white fluorescent light and the saturation dose for hypocotyl elongation was reportedly at 3.6 mmol m^{-2} d^{-1} (Gaba and Black, 1985). This is a comparable level to our near-saturation dose selected for the testing movable LED fixtures (4.0 mmol m^{-2} d^{-1}).

The non-linear regression using a Michaelis–Menten-type model (Fig. 2) showed that the interspecific squash seedlings examined in the present experiment had a greater maximum increase in hypocotyl length, V_{max} (30.3 mm) and a comparable K_M (1.4 mmol m^{-2} d^{-1}) than those quantified for tomato seedlings (9–23 mm for V_{max} and 0.5–1.7 mmol m^{-2} d^{-1} for K_M) when the EOD-FR treatments were applied in the same way (Chia and Kubota, 2010). This may be due to the difference in the degree of plant phytochrome-mediated response between the two species. In fact, cucurbits are widely used as model species in photomorphogenic studies and cucumber, a member of cucurbits, is considered highly responsive to EOD light treatments and therefore an ideal model species (Xiong et al., 2011).

3.2. EOD-FR treatment using movable vs. stationary light fixtures

The difference in hypocotyl length between the EOD-FR treatment and non-treated control seedlings was significant after three days of EOD-FR treatment, and became greater with increasing treatment days (Table 2). After the 5-day treatment, hypocotyl length of interspecific squash seedlings was 55–69% longer when EOD-FR treatment was applied using movable or stationary light fixtures, compared to that in the non-treated control. No significant differences were observed in hypocotyl length between the movable and stationary fixtures. Therefore EOD-FR light from moving light fixtures seems to be as effective as the EOD-FR light from the more conventional stationary fixtures. As far as we are aware, this is the first demonstration of the efficacy of EOD-FR light treatment using a movable light fixture.

3.3. One-way trip (slow speed) vs. two round trips (fast speed) of EOD-FR light application

Both EOD-FR treatments of one-way trip with slower traveling speed and two round trips (four applications) with faster speed elongated the interspecific squash seedlings to the same extent after 5 days of EOD-FR treatment (Table 3). This suggests that as long as the dose meets the minimum requirement, traveling speed

Table 2
Hypocotyl length (mm) of interspecific squash rootstock seedlings as affected by end-of-day far-red (EOD-FR) light treatments applied with a movable or stationary light fixture. The hypocotyl length before starting the treatment was 22.1 ± 0.16 mm (day 0). Data represent the means and standard errors of 6 replications (9 plants per replication).

Treatment	Days after start of EOD FR treatment				
	1	2	3	4	5
EOD-FR treatments					
Movable fixture	39.1 ± 3.7a[a]	58.7 ± 5.5a	69.8 ± 7.3a	79.0 ± 5.2a	82.2 ± 5.2a
Stationary fixture	39.0 ± 3.6a	62.0 ± 5.8a	75.1 ± 7.8a	85.6 ± 5.3a	89.6 ± 4.9a
Non-treated control	31.4 ± 2.6a	42.4 ± 3.7a	48.1 ± 4.8b	51.9 ± 4.2b	53.0 ± 3.9b

[a] ANOVA protected mean separation by LSD ($P < 0.05$).

Table 3
Effect of traveling speed of movable light (with corresponding application time) employed in the end-of-day far-red (EOD-FR) light treatment on the hypocotyl length of interspecific squash rootstock seedlings measured after five consecutive days of EOD treatment. Data represent the means and standard errors of 3 replications (9 plants per replication).

Traveling speed (application times)	Hypocotyl length (mm)
0.78 mm s^{-1} (one application per EOD)	73.6 ± 3.0a[a]
3.13 mm s^{-1} (four applications per EOD)	90.9 ± 7.1a

[a] ANOVA-protected mean separations by LSD ($P < 0.05$).

and application time can be modified, allowing more flexibility in designing EOD lighting in commercial operations.

To implement the use of movable light fixtures for EOD lighting in commercial greenhouses, additional considerations may be required. Growers may consider using a movable system similar to the conventional boom irrigation traveling over the canopy. Multiple applications during the night may be better than a one-time application when there is a chance of light contamination around the greenhouse. However, in the scale of a commercial greenhouse setting, the 'fast' speed of 3.13 mm s^{-1} examined in the present experiment is still slower than what would be needed to complete the EOD-FR treatment within a reasonable time frame after sunset. A speed of 3.13 mm s^{-1} would require 1.8–4.3 h to complete one application over a typical small greenhouse length of 20–50 m, for example. To complete FR application within 1 h, the minimum traveling speed would be 7–14 mm s^{-1}. Therefore, light output needs to be increased by 10–20 times of what was examined in the present experiment, in order to apply a practical speed and attain the EOD-FR dose with one application. Light output can be increased by installing more LEDs with higher light output in the horizontally traveling bar. Further experiments need to be conducted at a more practical speed (>7 mm s^{-1}) and a corresponding higher FR light intensity (> 40 μmol m^{-2} s^{-1} in average over the effective area) before designing a commercial application. Applications of movable high pressure sodium (HPS) lamps have been examined as supplemental lighting to promote plant photosynthesis and growth with various results (Blom and Zheng, 2006a,b; Marissen et al., 2006; Zheng et al., 2006). Blom and Zheng (2006b) found that there was no significant difference in plant growth (shoot dry weight) between movable and stationary HPS lamps for chrysanthemum and petunia but that plant growth was reduced with movable HPS lamps (at 2–20 mm s^{-1}) for tomato. The efficacy of movable light fixture for EOD treatment needs to be further examined using various plant species.

In the provision of EOD-FR lighting, as long as the same plant response is assured, use of movable fixtures may be preferable to distributing (and therefore wiring) many stationary light fixtures. Additionally stationary light fixtures have the disadvantage of shading the plants during the day. Another possible way of applying FR light with limited numbers of light fixtures is to use an oscillating parabolic reflector such as that examined with high pressure sodium lamps for the night interruption to control flowering (Blanchard and Runkle, 2010). For such applications, level of necessary FR light output of the light fixtures will be dependent on the dose requirement, the lamp oscillation cycle, and the number of lamp fixtures per greenhouse production space.

3.4. Effect of EOD-FR light treatment on hypocotyl diameter, fresh and dry weights of interspecific squash seedlings

Increasing EOD-FR light dose significantly increased stem fresh and dry weight of seedlings (by 40% and 30%, respectively; data not shown) but did not affect hypocotyl diameter (4.3–4.4 mm), fresh (2.5–2.7 g) and dry weight (0.21–0.23 g) of the cotyledons/leaves. Xiong et al. (2011) also demonstrated the dry matter increase for the stem extended by EOD-FR light treatment compared to that by EOD-R light treatment. In the movable light experiment, there were also no significant differences in hypocotyl diameter (3.4–3.7 mm) and shoot fresh (2.7–3.1 g/plant) and dry weights (216–224 mg/plant) between the treatments.

4. Conclusion

End-of-day FR light treatment successfully extended the hypocotyls of 'Tetsukabuto' interspecific squash seedlings. The length of hypocotyl increased with increasing FR light dose (intensity × duration) and the response was nearly saturated at a dose of 4.0 mmol m^{-2} d^{-1}. The seedlings responded in the same way when EOD-FR light was applied from a moving LED fixture regardless of the traveling speed examined in the present experiment (0.78 vs. 3.13 mm s^{-1}), compared with those under the stationary LED fixture. Since EOD FR light treatment requires relatively lower light dose (e.g., 4 mmol m^{-2} d^{-1} in our experiment), nearly one thousandth of those applied in photosynthetic supplemental lighting (>4 mol m^{-2} d^{-1} in general), growers may prefer a design with small numbers of movable, high-powered LED light fixtures. Commercial trials will help refine the design requirement for EOD-FR light treatment. Nevertheless, the results presented in this paper suggest that EOD-FR light treatment can be designed with greater flexibility in application methods.

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