Using Movable Light-emitting Diodes for Electricity Savings in a Plant Factory Growing Lettuce

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SUMMARY. In this study, the effects of light-emitting diode (LED) panels with different illumination schedules and mounted above butterhead lettuce (Lactuca sativa var. capitata) seedlings on lettuce growth and photosynthesis were examined, and the performance of the vertical and horizontal movable system on energy savings was evaluated. The illumination schedules used were fixed LED [F-LED (four LED panels illuminated the area below)] and movable LED [M-LED (two LED panels moved left and right once per day to illuminate the same area as F-LED)] at distances of 10 and 30 cm above the seedlings. The plant yields were uniform in all LED treatments. The highest light utilization efficiencies and lowest electricity consumption were found for the treatments with irradiation from a shorter distance above the seedlings. The true leaf numbers and ascorbic acid concentrations were the highest in the M-LED and F-LED treatments at a distance above the seedlings of 10 cm, while the leaf lengths and sucrose concentrations in these groups were significantly lower than those in the 30-cm treatment. These results indicate that illumination with M-LED can have the initial light source input while maintaining yield and that sustained illumination from a shorter distance above the seedlings is the main factor in electricity savings.

Plant factories with artificial lighting are widely used in many areas (Hahn et al., 1996; Ikeda et al., 1992; Ioslovich and Gutman, 2000; Kato et al., 2010; McAvoy et al., 1989; Morimoto et al., 1995) as an ideal model for precision agriculture (Murase, 2000), in which artificial lights play an important role in the precise control of the light environment. However, the widespread use of plant factories with artificial lighting is limited by their high initial investment and operation costs, which are mainly attributable to the costs of electricity for artificial lighting (Ohyama et al., 2001). With the continuous expansion of plant factories, reducing the initial investment and electric-energy consumption of artificial lighting has become increasingly important.

Several possible solutions for reducing the electricity consumption of lighting have been studied. Nishimura et al. (2001) estimated reductions of 50% in the electricity consumption of lamps by improving the efficiency of the lighting. Yamada et al. (2000) found that stepwise photosynthetic photon flux (PPF) control was a useful method for reducing the electricity consumption of lighting and increasing the electricity utilization efficiency. Bao et al. (2008) integrated a photovoltaic power generating system into a plant factory to reduce dependence on the commercial grid. However, these solutions either have limited effects on electricity savings or are associated with high costs of equipment construction.

As an attractive alternative to traditional light sources, LEDs have been widely used in potential energy saving applications such as rooms (Ryckaert et al., 2012), supermarkets (Elsevier Science, 2006), tunnels (Zeng et al., 2011), and even in coastal fishing boats (Matsushita et al., 2012).

Because of their tailorability of spectral composition, wavelength specificity, and narrow bandwidth, LEDs have been widely used to examine the effects of different environmental light parameters on plant growth, phytochemical processes, or both. Kitaya et al. (1998) found that the leaf number of lettuce increased with increasing PPF. The phenolic concentration of lettuce has been reported to increase by 6% under supplemental red light, while supplemental far-red light decreased anthocyanin, carotenoid, and, chlorophyll (Chl) concentrations by 40%, 11%, and 14%, respectively (Li and Kubota, 2009). Green-light supplementation has been reported to stimulate a rapid increase in the growth rate of etiolated arabidopsis seedlings [Arabidopsis thaliana (Folta, 2004)], ascorbic acid accumulation (Samuoliene et al., 2012), and lettuce growth (Kim et al., 2004), but showed a negative effect on biomass production (Folta and Maruhnich, 2007). Previous studies have also indicated that blue light is essential for leaf expansion and biomass...
production (Hogewoning et al., 2010; Johkan et al., 2012; Li et al., 2010) and also plays an important role in Chl synthesis (Kurilčík et al., 2008; Li et al., 2012; Poudel et al., 2008; Senger, 1982), but the much higher blue fraction in fluorescent lamps (FL), compared with high-pressure sodium lamps, incandescent lamps, and LEDs, may not effectively interact with the plant (Dougher and Bugbee, 2001). Li and Kubota (2009) have shown that the ascorbic acid concentration in lettuce is sensitive to none of the abovementioned spectra of light, reaching the opposite conclusion of Ohashi-Kaneko et al. (2007), who reported that the ascorbic acid content in leaf lettuce increased under irradiation by blue or red-blue light. However, few studies have focused on the electricity savings of LEDs.

A movable system was built for this study, and its benefits were evaluated by analyzing the electricity consumption of the lighting as well as the plant growth, plant physiology, and phytochemical accumulation of the lettuce grown under different lighting modes. The objective of this research was to develop a lighting system for lettuce production in a plant factory by halving the electric input of the original light sources while providing high PPF with low electricity consumption and maintaining lettuce yield and quality.

Materials and methods

Plant materials and growth conditions. Butterhead lettuce seeds were sown in a plastic seedling tray (57 × 23.5 × 4 cm) containing a substrate mix of 1 part:1 vermiculite (by volume), germinated in a tempered glass covered greenhouse at the Chinese Academy of Agricultural Sciences (CAAS), Beijing, China (lat. 39°57′34.89″N, long. 116°19′13.03″E) under ambient light and irrigated with tap water once per day. When the first true leaf (≈5 mm in length) appeared ≈15 d after sowing, nine uniform seedlings were selected and transplanted onto cultivation boards (polyethylene, 110 × 60 × 14 cm, 18 plants/m²) in an 25-m² industrial computer-controlled, fully closed plant factory at CAAS, Beijing, China (lat. 39°57′35.09″N, long. 116°19′12.71″E) and were cultivated with the deep flow technique (Hu et al., 2008) for 30 d and maintained under a 10-h photoperiod (Wen, 2009). The air temperature was maintained at 20 °C, while the mean temperature measured at the top of the canopy in each treatment described below was (±SE) 23.5 ± 0.5/21 ± 0.5 °C (light/dark cycle), synchronized with the operation of the light sources. The humidity was 60% to 80%, and the carbon dioxide concentration was kept consistent with the atmosphere by ventilating at a rate of one air exchange every 3.5 h during the day and every 5 h at night. Fresh nutrient solution [(±SE) pH 6.3 ± 0.1, EC 1.6 ± 0.1 mS·cm⁻¹] was circulated for 15 min every 12 h. The air temperature and humidity were measured twice per day; the parameters of the nutrient solution were monitored daily.

Light treatments. A movable system (Delta Electronics, Taipei, China) was built (Fig. 1); the system was composed of a movable metal frame (125 × 60 × 80 cm) driven by two groups of programmable motion control servo motors, which provided automatic horizontal and vertical movement. Custom-manufactured LED panels (60 × 25 × 1.2 cm; FHT Co., Shenzhen, China) with red (peak at 630 nm) and blue (peak at 460 nm) LEDs were used as the main light source and were placed horizontally 10 or 30 cm above the seedlings inside the plant factory to obtain the illumination schedule described below. The light treatments examined in this experiment are shown in Table 1 and Fig. 2 and included T8 FL (YZ18RR26, 18 W each, electrical ballast NEB118/T8-EM, power factor = 0.98; NVC Co., Huizhou, China) as the control [FL (Fig. 2A)], four LED panels fixed 30 cm directly above the seedlings [F-LED30 (Fig. 2B)], two LED panels attached to the movable metal frame 30 cm above the seedlings [M-LED30 (Fig. 2C)], two LED panels attached to the movable metal frame 10 cm above the seedlings [M-LED10 (Fig. 2D)], and four LED panels fixed 10 cm directly above the seedlings [F-LED10 (Fig. 2E)]. The FLs in control were covered with an aluminum foil reflector. The red-blue ratio (R/B) for all LED panels was kept at 8:1 (Wen, 2009). Each treatment and control covered 0.5 m² (completely covering the growing area of the plants below), and spectral energy distribution scans were recorded at 400 to 800 nm with 2-nm steps of the LEDs and FL (Fig. 3) with a calibrated fiber optic spectrometer (Avaspec-2048; Avantes, Apeldoorn, The Netherlands) placed horizontally under the light sources used for the experiments.

The FL and F-LED30 employed the light sources hanging 30 cm above the seedlings to simulate the current cultivation mode widely used in plant factories. The PPF 15 cm from the lighting panels were kept at 150 μmol·m⁻²·s⁻¹; the illumination times were 10 h per day (0700 to 1700 HR).

To halve the investment of light sources, the M-LED30 employed two LED panels hanging 30 cm
Table 1. Light environment parameters, including composition of light sources, distance between the light source and the lettuce, lighting time, light intensity, fraction and ration of different spectral of lights and daily light integral (DLI) of treatments with fluorescent lamps (FL) as the control, four light-emitting diode (LED) panels fixed 30 cm (11.8 inches) directly above the seedling (F-LED30), two LED panels attached to the movable system 30 cm above the seedlings (M-LED30), two LED panels attached to the movable system 10 cm (3.9 inches) above the seedlings (M-LED10), and four LED panels fixed 10 cm directly above the seedlings (F-LED10).

| Parameter                     | M-LED10          | F-LED10         | M-LED30          | F-LED30          | FL               |
|-------------------------------|------------------|-----------------|------------------|------------------|------------------|
| Lighting sources*             | LED panel × 2    | LED panel × 4   | LED panel × 2    | LED panel × 4    | T8 tube × 8      |
| Height (cm)#                  | 10               | 10              | 15               | 15               | 15               |
| Lighting time (h·d⁻¹)         | 10 × 2           | 10              | 10 × 2           | 10               | 10               |
| Light intensity (µmol·m⁻²·s⁻¹) |                  |                 | 150              | 150              | 150              |
| PPF (400–700 nm)              | 17               | 17              | 17               | 17               | 17               |
| Blue (400–500 nm)             | 0                | 0               | 0                | 0                | 63               |
| Green (500–600 nm)            | 133              | 133             | 133              | 133              | 39               |
| Red (600–700 nm)              | 0                | 0               | 0                | 0                | 7                |
| Far-red (700–800 nm)          | 0                | 0               | 0                | 0                | 7                |
| DLI (mol·m⁻²·d⁻¹)            | 12.96            | 12.96           | 4.32 to 12.96    | 4.32 to 12.96    | 4.75 to 10.97    |
| Fraction (%)                  |                  |                 |                  |                  |                  |
| PPF                           | 100              | 100             | 100              | 100              |                  |
| Blue                          | 11               | 11              | 11               | 11               | 32               |
| Green                         | 0                | 0               | 0                | 0                | 42               |
| Red                           | 89               | 89              | 89               | 89               | 26               |
| Ratios (µmol·µmol⁻¹)          |                  |                 |                  |                  |                  |
| Red:far-red                   | Infinite         | Infinite        | Infinite         | Infinite         | 5.6              |
| Red:blue                      | 7.8              | 7.8             | 7.8              | 7.8              | 0.8              |

*The x2, x4, and x8 indicate two, four, and eight units of each lighting source.

†The distance from the light source where the specific photosynthetic photon flux (PPF) is detected; 1 cm = 0.3937 inch.

‡The x2 indicate both the left and right side was exposed to a 10-h photoperiod each.

§The PPF under designated height of each treatment.

The DLI value were calculated based on periodic measurements, and increased with the growth of lettuce, while the light sources were anchored 30 cm above the seedling from the beginning of the experiments.

above the seedlings, the PPF 15 cm from the lighting panels were kept at 150 µmol·m⁻²·s⁻¹; the illumination time was 20 h per day (0700 to 1700 HR and 1900 to 0500 HR).

For further improvement of current cultivation mode, the M-LED10 was conducted, in which the distance between the top of the seedlings and the lighting panels were kept at 10 cm by manually elevating the metal frame once every 1 to 2 d according to the growth rate of the lettuce at different growth stages. The PPF (150 µmol·m⁻²·s⁻¹) were set up with no changes by adjusting the luminous intensity of the individual LEDs. The illumination time was 20 h per day (0700 to 1700 HR and 1900 to 0500 HR).

To decide if the distance is the only major factor affecting plant growth, the F-LED10 is added. Four LED panels were kept at 10 cm manually. The PPF (150 µmol·m⁻²·s⁻¹) were set up with no changes by adjusting the luminous intensity of the individual LEDs. The illumination time was 10 h per day (0700 to 1700 HR).

The planters below M-LED10 and M-LED30 were carefully divided into the left half and right half sides by black films to ensure that no light spilled over from one side to the other; half the number of LED panels were attached to the metal frame and underwent a horizontally back and forth motion to the left or to the right once over several minutes every 12 h regardless of the speed (Fig. 1 and Table 1), illuminating the same plant area as in the F-LEDs while providing light for 20 h per day (0700 to 1700 HR and 0500 to 0000 HR). The illumination was conducted, in which the distance between the top of the seedlings and the lighting panels were kept at 30 cm above the seedling from the beginning of the experiments.

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electricity meter (LCDG-ZJ120–01; LiChuang Science and Technology Co., Laiwu, China) was employed to measure the electricity consumption of the lighting (the energy costs for cooling, ventilation, and the recirculation of the nutrient solution were not considered during our experiments). The light utilization efficiency [LUE (grams per kilowatt hour)] of each treatment was determined [LUE = leaf FW (grams per plant) × 18 plants/m²/electric energy consumption of lighting (kilowatts per hour)]. Fresh leaf tissue (2 g) was extracted in 20 mL of 80% acetone/water (v/v) overnight at 4°C in the dark. The extract was centrifuged (3K15; Sigma Laborzentrifugen, Osterode am Harz, Germany) at 10,000 g for 10 min, and the supernatant was used for the spectrophotometric determination of chlorophyll a (Chl a) and chlorophyll b (Chl b) with a spectrophotometer.

Fig. 2. The light treatments examined in the present experiment composed of (A) T8 fluorescent lamps as the control (FL), (B) four light-emitting diode (LED) panels fixed 30 cm directly above the seedlings (F-LED30), (C) two LED panels attached to the movable metal frame 30 cm above the seedlings (M-LED30), (D) two LED panels attached to the movable metal frame 10 cm above the seedlings (M-LED10), and (E) four LED panels fixed 10 cm directly above the seedlings (F-LED10). The large arrows indicate the horizontal moving directions (left and right) and vertical moving directions; PPF = photosynthetic photon flux, 1 cm = 0.3937 inch.

Fig. 3. Spectral distributions of light from light-emitting diode (LED) and fluorescent lamps (FL) measured with a fiber optic spectrometer (AvaSpec-2048; Avantes, Apeldoorn, The Netherlands), and plant absorption spectrum (PAS) reported by Sager et al. (1982); PPF = photosynthetic photon flux.
Table 2. Electricity consumption of lighting, plant yields and light utilization efficiencies (LUEs) of lettuce under fluorescent lights, the F-LED (F-LED10, F-LED30) and M-LED (M-LED10, M-LED30) consumed much less (29.4% to 42.4%) electricity than the FL, and the plant yield increased significantly (Table 2). Benefiting from their decreased distance to the plants, the M-LED10 and F-LED10 achieved further reductions (15.0% to 18.4%, respectively) in energy consumption and 20.0% to 18.5% increase in LUE relative to M-LED30 and F-LED30, respectively, allowing the plants to obtain the desired illumination with minimal energy consumption.

However, considering the light uniformity under the LED panels, there was a minimum distance between LED panels and plant, which was determined by the luminescence angle of LEDs. Specific to the LED panels we used in our research, the minimum distance, also the optimal photoperiod, was 10 cm (3.9 inches) above the seedling (M-LED10), and four LED panels fixed 10 cm directly above the seedling (M-LED30), two LED panels attached to the movable system 30 cm (11.8 inches) above the seedlings (F-LED30), two LED panels attached to the movable system 10 cm (3.9 inches) above the seedlings (F-LED10), and four light-emitting diode (LED) panels fixed 30 cm (11.8 inches) above the seedlings of lettuce (F-LED10). The electricity consumptions were recorded with an electricity meter.

| Treatment | Electricity consumption (kWh/m²) | Plant yields [mean ± sd (g·m⁻²)] | LUEs [mean ± sd (g/kWh)] |
|-----------|---------------------------------|----------------------------------|--------------------------|
| M-LED10   | 61.2                            | 625.9 ± 9.2 a                    | 10.2 ± 0.2 a             |
| F-LED10   | 60.5                            | 620.1 ± 35.8 a                   | 10.2 ± 0.6 a             |
| M-LED30   | 74.1                            | 629.8 ± 13.2 a                   | 8.5 ± 0.2 b              |
| F-LED30   | 72                              | 621.9 ± 6.4 a                    | 8.6 ± 0.1 b              |
| FL        | 105                             | 438.7 ± 15.8 b                   | 4.2 ± 0.2 c              |

*Calculated based on the power consumption of each treatment; 1 kWh/m² = 0.0929 kWh/ft².
*Calculated based on the leaf fresh weight (FW) of each treatment; 1 g·m⁻² = 0.0033 oz/ft².
*Light utilization efficiencies were estimated by dividing the yield (g·m⁻²) by electricity consumption of lighting per area; 1 g/kWh = 0.0353 oz/kWh.
*Data were analyzed by analysis of variance, and different letters within the column indicate significant differences at P ≤ 0.05 according to least significant difference test.

Table 2. Electricity consumption of lighting, plant yields and light utilization efficiencies (LUEs) of lettuce under fluorescent lamps (FL), four light-emitting diode (LED) panels fixed 30 cm (11.8 inches) directly above the seedling (F-LED30), two LED panels attached to the movable system 30 cm above the seedlings (M-LED30), two LED panels attached to the movable system 10 cm (3.9 inches) above the seedlings (M-LED10), and four LED panels fixed 10 cm directly above the seedlings (F-LED10). The electricity consumptions were recorded with an electricity meter.
distance, is 10 cm. For the FL, considering the heat they released to the canopy, 10-cm treatment was not employed.

M-LED10 consumed almost the same amount of energy as did F-LED10, as well as in M-LED30 and F-LED30. It might be because the total light energy uses of M-LED10 and M-LED30 were doubled due to the illumination duration, which was twice as long as in the corresponding fluorescent treatments. This increased illumination duration was offset by halving the LED panels employed in the experiment through the movable system, illustrating that the reduced energy consumption contributed to a lower luminous intensity, as did the reduction in distance. To manifest the profits of the movable system in reducing the initial investment cost of the light sources, an improved movable system was built. The $40 device could provide the same function as the prototype used in the experiments, considerably reducing the investment cost according to the price of light sources used.

**PLANT GROWTH.** The lettuce growth was significantly affected by different DLI’s in treatments with different PPF on plant canopy. For the treatments (M-LED10 and F-LED10) employed a fixed distance of 10 cm above the plants, sustained PPF of 150 μmol·m⁻²·s⁻¹ resulted in a constant high DLI value of 12.96 mol·m⁻²·d⁻¹. For the treatments (M-LED30 and F-LED30) provided variable PPF at different growth stages (50 μmol·m⁻²·s⁻¹ early, 150 μmol·m⁻²·s⁻¹ late) with the increase of plant height, variable DLI values were ranged from 4.32 to 12.96 mol·m⁻²·d⁻¹ (Table 1). Notable positive effects were observed in all LED treatments (Table 3). This may be explained by the beneficial effects of higher red light fraction and R/B in LED light sources, as well as the negative effect of green light on biomass production in FL (Folta and Childers, 2008). The blue light fraction in FL may be too high to induce beneficial effects on plant growth, in previous study (Dougher and Bugbee, 2001), overhigh blue fraction may not effectively interact with the plant.

All parameters were not significantly different between M-LED10 and F-LED10 as well as between M-LED30 and M-LED30 (Table 3), suggesting that the DLI might be the main effect variable on plant growth. The reversed photoperiod provided by the different illumination schedules in our study had no significant effects on plant growth.

The true leaf number and leaf length displayed opposing trends under M-LED10 and F-LED10 as well as between M-LED30 and M-LED30 (Table 3), suggesting that the DLI might be the main effect variable on plant growth. This was most likely due to the low radiation use efficiency caused by the mutual shading by the leaves within the plant canopy and the high respiration cost of the production and maintenance of leaves (Tei et al., 1996).

**PHYTOCHEMICAL ACCUMULATION.** The phytochemical concentrations in the lettuce leaves were significantly affected by the different light treatments (Table 4). Chl a was present in similar concentrations in all of the treatments and appeared to be synthesized at a higher rate than Chl b, perhaps because of the wider absorption spectrum of the Chl a pigment. Furthermore, the applied PPF level reached the minimal PPF essential for Chl a saturation synthesis.

The Chl b concentration was greatest under FL, at 28.6% more than in all LED treatments, possibly because the high PPF of blue light in FL (Table 1) plays an important role in Chl synthesis, as discussed in previous results (Kurilčík et al., 2008; Li et al., 2012; Poudel et al., 2008; Senger, 1982). High utilization efficiency under LED lights (Saebo et al., 1995) and a “dilution” effect because of the enhancement of DW (Li and Kubota, 2009) may also be possible.

The sucrose concentrations of M-LED30 and F-LED30 increased by 49.6% and 48.5% (Table 4), respectively, compared with the corresponding M-LED10 and F-LED10. The fructose and glucose concentrations were similar among all treatments. As a desirable parameter in

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**Table 3. Lettuce fresh weight (FW), plant height, true leaf number and leaf length for lettuce under fluorescent lamps (FL), four light-emitting diode (LED) panels fixed 30 cm (11.8 inches) directly above the seedling (F-LED30), two LED panels attached to the movable system 30 cm above the seedlings (M-LED30), two LED panels attached to the movable system 10 cm (3.9 inches) above the seedlings (M-LED10), and four LED panels fixed 10 cm directly above the seedlings (F-LED10).**

| Treatment    | Leaf FW [mean ± SD (g)] | Plant ht [mean ± SD (cm)] | True leaves [mean ± SD (no.)] | Leaf length [mean ± SD (cm)] |
|--------------|-------------------------|----------------------------|-------------------------------|-------------------------------|
| M-LED10      | 34.8 ± 0.5 a            | 15.4 ± 0.3 a               | 23.2 ± 0.3 a                  | 15.6 ± 0.2 b                 |
| F-LED10      | 35.4 ± 1.1 a            | 15.1 ± 0.3 a               | 22.8 ± 0.3 a                  | 15.1 ± 0.5 b                 |
| M-LED30      | 34.6 ± 0.8 a            | 15.6 ± 0.2 a               | 21.2 ± 0.2 b                  | 17.2 ± 0.3 a                 |
| F-LED30      | 34.5 ± 1.9 a            | 15.4 ± 0.2 a               | 21.6 ± 0.3 b                  | 17.5 ± 0.3 a                 |
| FL           | 24.4 ± 0.9 b            | 13.5 ± 0.4 b               | 16.9 ± 0.2 c                  | 12.4 ± 0.2 c                 |

*1 g = 0.0353 oz, 1 cm = 0.3937 inch.

*Data were analyzed by analysis of variance, and different letters within the column indicate significant differences at P ≤ 0.05 according to least significant difference test.*
Table 4. Concentrations of chlorophyll a (Chl a), chlorophyll b (Chl b), fructose, glucose, sucrose, and ascorbic acid of lettuce under fluorescent lamps (FL), four light-emitting diode (LED) panels fixed 30 cm (11.8 inches) directly above the seedling (F-LED30), two LED panels attached to the movable system 30 cm (11.8 inches) above the seedlings (M-LED30), two LED panels attached to the movable system 10 cm (3.9 inches) above the seedlings (M-LED10), and four LED panels fixed 10 cm (3.9 inches) directly above the seedlings (F-LED10).

| Treatment   | Chl a [mean ± SD (mg-g⁻¹ FW)] | Chl b [mean ± SD (mg-g⁻¹ FW)] | Fructose [mean ± SD (mg-g⁻¹ DW)] | Glucose [mean ± SD (mg-g⁻¹ DW)] | Sucrose [mean ± SD (mg-g⁻¹ DW)] | Ascorbic acid [mean ± SD (mg-g⁻¹ DW)] |
|-------------|--------------------------------|--------------------------------|----------------------------------|---------------------------------|---------------------------------|-------------------------------------|
| M-LED10     | 0.25 ± 0.00 a                  | 0.14 ± 0.01 b                  | 21.32 ± 3.00 a                   | 9.06 ± 1.64 a                   | 25.56 ± 1.39 b                  | 2.29 ± 0.16 a                       |
| F-LED10     | 0.25 ± 0.01 a                  | 0.18 ± 0.02 a                  | 20.82 ± 2.18 a                   | 8.89 ± 0.56 a                   | 26.78 ± 0.96 b                  | 2.11 ± 0.33 a                       |
| M-LED30     | 0.25 ± 0.00 a                  | 0.15 ± 0.01 b                  | 16.35 ± 1.89 a                   | 8.69 ± 0.62 a                   | 39.83 ± 2.24 a                  | 1.06 ± 0.15 c                       |
| F-LED30     | 0.25 ± 0.01 a                  | 0.18 ± 0.02 a                  | 17.05 ± 2.21 a                   | 8.75 ± 1.05 a                   | 30.32 ± 3.48 b                  | 1.48 ± 0.01 b                       |
| FL          | 0.25 ± 0.00 a                  | 0.18 ± 0.02 a                  | 17.03 ± 3.31 a                   | 9.40 ± 1.33 a                   | 38.28 ± 1.38 a                  | 1.48 ± 0.01 b                       |

FW = fresh weight, DW = dry weight; 1 mg g⁻¹ = 1000 ppm.

Data were analyzed by analysis of variance, and different letters within the column indicate significant differences at P \leq 0.05 according to least significant difference test.

terms of food quality (Lin et al., 2013) and the most sensitive response to primary photosynthesis production (Lefsrud et al., 2008), sugars are not only the direct products of photosynthesis storage, accumulation, and transportation but also the primary substrates of respiration. The higher the sucrose levels, the less fructose and glucose were observed in all treatments in this study; it may be because the sugar concentrations in plant tissue rely on the balance between their synthesis and consumption. The low sucrose concentrations in M-LED10 and F-LED10 may indicate that the constant high PPF kept the plants at a high photosynthetic rate and that the sucrose might decompose into fructose and glucose, as shown in Table 4.

In contrast to previous studies (Li and Kubota, 2009), the ascorbic acid concentrations in F-LED10 and M-LED10 increased by 42.6% and 54.7%, respectively, but were reduced by 28.4% and 34.5% in F-LED30 and M-LED30 compared with the FL treatment, respectively (Table 4). Neither result is completely in accordance with the report that the ascorbic acid content in leaf lettuce is significantly increased under supplemental red and blue LED light when compared with white FL (Ohashi-Kaneko et al., 2007) nor do these results completely contradict the conclusion that the supplemental green light component had a significant positive effect on ascorbic acid accumulation (Samuoliene et al., 2012). The results of our study may be explained by the interaction effect between PPF and green light. Throughout the growth period, the constant high PPF of M-LED10 and F-LED10 produced an even greater impact on the ascorbic acid accumulation than did the green light in FL (Table 1), whereas the increased PPF in M-LED30 and F-LED30 did not reach an adequate density to bring about an equal effect due to green light. The crucial stage of growth for inducing PPF, green light, or both may also be a factor.

Conclusions

Our results demonstrated that the illumination schedule employed in this study (M-LED10 and M-LED30) can halve the initial light source input while resulting in no differences in electricity consumption, morphological parameters, or phytochemical accumulation compared with F-LED10 and F-LED30. Irrespective of the illumination schedule, the DLI value determined by the distance between light source and lettuce played an important role in the electricity savings and plant quality. As demonstrated by M-LED10 and F-LED10, a consistently high PPF and lower luminous intensities resulted in massive electricity savings and significant increases in the true leaf number and ascorbic acid concentrations compared with those under increasing PPF (M-LED30 and F-LED30). A shorter illumination distance did not always have positive effects as reductions in the leaf length and sucrose concentration were observed. We conclude that the use of M-LED systems in plant factories with artificial lighting will bring about considerable economic benefits due to the lower light source input and reduced electricity consumption in addition to increasing plant production. Although only crops that are tolerant to photoperiods of 12 h or less can be cultivated by this method, many species suitable for plant factories are nonetheless available.

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