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Research Article

Effect of artificial light sources on the growth of green oak lettuce (*Lactuca sativa* L.) grown in plant factories

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Abstract
Artificial light sources in plant factories offer numerous advantages over traditional plant production. Optimal artificial lighting systems will provide sufficient light to promote plant growth. Thus, this study aimed to determine different artificial light sources on plant growth, especially on internode length, root length, potassium (K), Calcium (Ca), and magnesium (Mg) contents of green oak lettuce (*Lactuca sativa* L.). Three artificial light sources were utilized in the plant factory: a fluorescent lamp (FL) typically used in plant factories and two light-emitting diodes (LED): bulb-LED and bar-LED lamps. Alternate periods of 12 h of light and dark were applied to the used factories. The results indicated that the lettuce grown under bulb-LED irradiation exhibited the lowest internode length and highest root length of green oak lettuce, regardless to light intensity and the higher photosynthetic photon flux density (PPFD) values of bulb-LED at the growing stage. K, Ca, and Mg contents in the lettuce shoot decreased in the order of K > Ca > Mg for all artificial light sources. The highest K, Ca, and Mg contents were 14.77±3.08, 4.77±0.92 and 108.14±9.36 mg/g dried weight (DW) obtained in lettuce grown under FL irradiation. Lower FL light intensity promotes nutrient deficiency, resulting in increased plant uptake. There was no significant difference in nutrient content between plants grown with bulb-LED and bar-LED. The K/Ca and K/Mg mole ratios were lowest in plants grown under FL irradiation. These findings suggest that FL can be used to control lettuce nutrient levels, whereas bulb-LED can be used to control lettuce growth.

Keywords: Hydroponic, *Lactuca sativa* L., Light spectrum, Morphology, Plant factory

INTRODUCTION

Plant factories are a well-known agricultural technology that allows plants to grow vertically in an indoor area using an artificially controlled system all year round. A soilless, temperature- and moisture-controlled and pesticide-free system enables the quick production of large quantities of high-quality plants. Artificial light sources are used instead of natural light for plant growth; they play a significant role in plant morphological and physiological characteristics by increasing crop yield and enhancing nutritional value (Orsini *et al*., 2020). Several artificial light sources have been developed to produce suitable wavelengths for plant growth. Fluorescent lamps (FLs) are more widely used due to their low electricity consumption and broad-spectrum emission (Dutta Gupta and Agarwal, 2017; Tabbert *et al*., 2021). However, light-emitting diodes (LEDs) have emerged as promising artificial light sources because of the single spectrum, long lifetime, directional light emission, and low heat production (Rehman *et al*., 2017). The significantly higher level of photosynthesis, phytochemical composition, and mineral elements (K, Fe, Zn, Cu, and Mn) is illustrated in lettuce grown under various LED light sources, especially in red LED (Amoozgar *et al*., 2017). LEDs are also used as a supplementary artificial light source in plant factories due to the several advantages compared to traditional fluorescence illumination (Camejo *et al*., 2020). Zhang *et al*. (2018) reported that artificial lighting with a photosynthetic photon flux density of 250 μmol/m^2·s with a light period of 16 h/d under R: B-LED ratio of 2.2 is a suitable light environment for the maximum growth and quality of lettuce (cv. Ziwei) production. Etae *et al*. (Etae *et al*., 2020) investigated green oak lettuce's growth and phytochemical content (*Lactuca sativa* L.) under fluorescent, bar-LED, and bulb-LED. They found that bar-LED enhances growth, phytochemical content, and energy efficiency. The key characteristics of artificial light used in plant factories, such as intensity, photoperiod, and wavelength, have been optimized by Urrestarazu *et al*. (Urrestarazu *et al*., 2016). Lettuce is widely consumed, increasing annual global demand (Tham *et al*., 2021). Purchases of lettuce are based on morphological appearance, particularly color and shape. Several studies have also investigated the impact of various artificial irradiation strategies and environments on lettuce growth and bioactive compounds (Cho *et al.*, 2020; Modarelli *et al.*, 2022; Mohamed *et al.*, 2021). Meanwhile, internode stem length, essential in economic traits using different light sources, remains limited (Son *et al.*, 2018). Thus, this study aimed to determine the effects of three artificial light sources on the growth of green oak lettuce in a plant factory setting, precisely the harvested plants' internode length, root length, and nutrient (K, Ca, and Mg) contents.

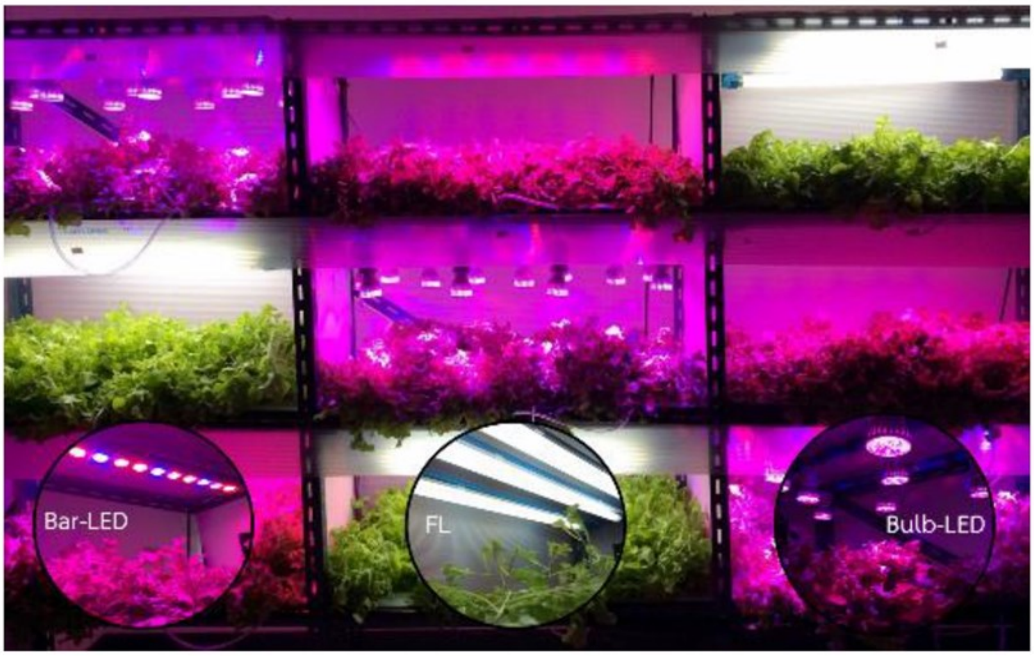
MATERIALS AND METHODS

Planting and growing conditions

Green oak lettuce (*Lactuca sativa* L.) seeds from Toltec farms (Phuket, Thailand) were germinated in tissue paper at 20°C for three days. They were then transferred into a polyfoam cube (2.5×2.5×3.0 cm) and accommodated in a nursery for 15 days. The plant sprouts were subsequently transplanted in the plant factory (Fig. 1). Each plant had a 20 cm×20 cm 'clear' area, where the light source was placed 25 cm above the plant. The deep flow technique was applied to this growing system, while aquarium-type air compressors and sandstones were applied to aerate the nutrient solution, which was set up as described by Sirinupong (Sirinupong, 2017) with electrical conductivity of 2.0 mS/cm, pH 6.0 and temperature at 28-30°C range. In all the experiments, the ambient temperature and relative humidity were kept at 28-30°C and 75-85 %, respectively. The systems were illuminated for 12 hours daily in daylight and darkness. The airflow produced by a fan was used to regulate the temperature in the growth chamber. After two weeks of transplanting, the lettuce was harvested for 35 days.

Light treatment

A completely randomized design was implemented. Light treatment consisted of three types of artificial light sources (Fig. 2). The first light source was the bar-LED



(a) (b) (c)

Fig. 1. *Plant factory system relying on deep flow technique and three different artificial light sources: (a) bar-LED, (b) FL and (c) bulb-LED; Plant factory was divided into 9 partitions; Each light source was utilized in three partitions*

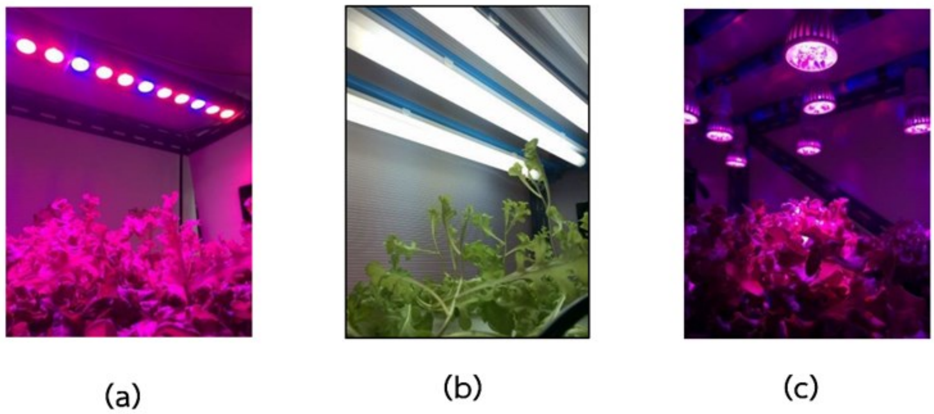


Fig. 2. *Artificial lighting set-up: (a) bar-LED, (b) FL and (c) bulb-LED*

(Ting-Mao Technology, Taiwan (30 W)), which can generate blue (460 nm) and red (630-660 nm) lights in the intensity ratio of blue (460 nm) 1: red (630 nm) 1: red (660 nm) 1. The second light source was the FL (TOSHIBA (18 W)), which produces light in the 380-700 nm range. The third was the bulb-LED (Ting-Mao Technology (4W)), which can generate blue (460 nm) and red (630-660 nm) lights in the intensity ratio of blue (460 nm) 2: red (630 nm) 1: red (660 nm) 1. The photosynthetic photon flux density (PPFD) values of bar-LED, FL, and bulb-LED were 111.33, 35.76 and 44.98 μmol/m^2s, respectively (Etae *et al*., 2020).

Sample collection

The lettuce was harvested from the growing bed (each bed had 11 plants) and washed in distilled water. Six replications were used. The root was cut out to determine the root length, and the stem was cut to measure the internode length. The lettuce samples were cleaned with distilled water and dried at 65°C for 1 week. The dried samples were ground finely, sieved through a 20-40 mesh sieve, and stored at 65°C for further analysis. The green oak lettuce used in this study is shown in Fig. 3 and 4.

Quantification of K, Ca, and Mg

Plant samples were digested using a wet digestion method modification adapted from Huang *et al*. (Huang *et al*., 2004). Plant sample 0.25 g was placed in a 50 mL digestion tube. The tube was then added with 10 mL of a 2:1 (v/v) mixture of HNO_3:$HClO_4$ and put in a digestion block (Environmental Express, HotBlock, UK) at 150°C. The block's temperature was then increased to 220°C for 1 h. After the sample solution had cleared, it was allowed to cool to room temperature in a fume hood. The digested sample was diluted with deionised water up to a final volume of 50 mL. KCl, $CaCl_2$, and $MgCl_2$ were used as standards for determining the concentrations of K^+, Ca^{2+}, and Mg^{2+}, respectively. A Perkin Elmer Analyst 100 Atomic Absorption Spectrometer, AAS (PerkinElmer, USA) was employed to determine the concentrations of three nutrients (K, Ca, and Mg) (Kalra, 1997). A hollow cathode lamp was used as a radiation source. The flow rate ratio of air: acetylene was 15:2 L/min while that of the fuel: oxidant in the ratio of 3:10 was used.

RESULTS AND DISCUSSION

Artificial light is an important environmental factor that promotes plant growth, particularly physiological and metabolic processes. LEDs provide economic and psychological advantages compared to traditional fluorescence illumination and have been widely used as a supplementary light source in plant factories. Thus, this study demonstrates the effect of two LED artificial light sources (Bar and Bulb LED) on green oak lettuce growth compared to traditional FL.

Internode length and root length

The artificial light source used to illuminate the plants for 35 days significantly affected the internode length and root length of green oak lettuce at the harvesting stage (Fig. 5). The internode length of lettuce grown under FL irradiation was significantly greater than those obtained under bar-LED and bulb-LED (Fig. 5a). In contrast, the longest root length was observed in a plant grown under bulb-LED irradiation, as shown in Fig. 5b. Large values of the plant stem's internode length indicate that the applied illumination provides insufficient light for photosynthesis, resulting in a significant decrease in plant leaf number. Fig. 5a shows that the plant grown under FL irradiation had a long stem. Since FL provides a broad wavelength spectrum (380-700 nm) and low intensity of red light, this may result in a lower rate of photosynthesis (Ruangrak and Khummueng, 2019) and less heat transfer from the lamp. Therefore, extending the stem is an option for the plant to survive in such conditions. Long roots (Fig. 5b) indicate efficient photosynthesis, increasing leaf number and suitable physiological traits for supporting plant growth. The light spectra of blue (450 nm) and red (660

(a) (b) (c)

Fig. 3. *Morphology of green oak lettuce grown under (a) longest stem and internode lengths of green oak lettuce grown under FL, (b) shape of green oak lettuce in quality traits when grown under bulb-LED and (c) shorter stem extensions of green oak lettuce grown under bar-LED.*

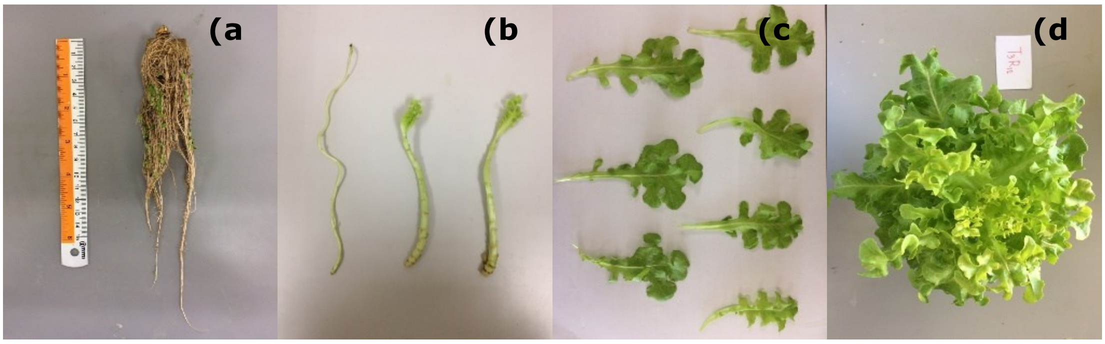


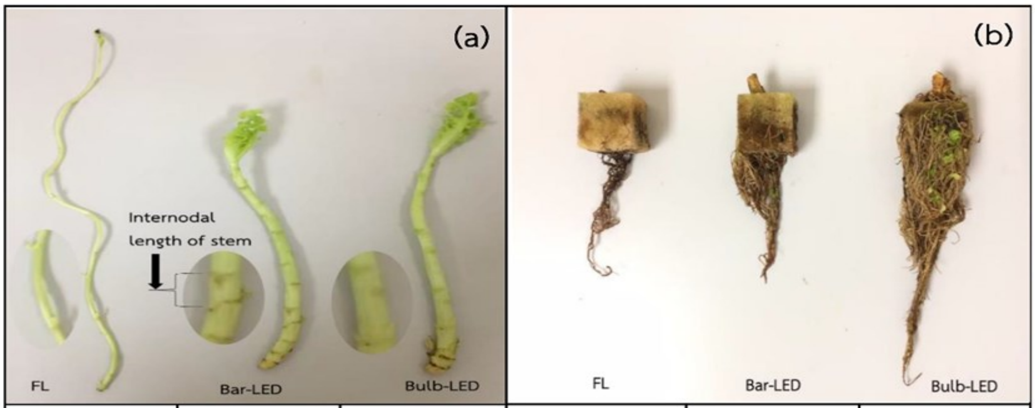
Fig. 4. *Green oak lettuce grown in this study: (a) root, (b) stem, (c) leaves and (d) canopy*

nm) are known to play a significant role in the photosynthetic process, which enhances plant growth (Tarakanov *et al*., 2022). In this study, bar-LED and bulb-LED were found to be more effective than FL in plant growth. The light emitted by bar-LED and bulb-LED contained wavelengths in blue and red in the following intensity ratios: 1 blue (460 nm): 1 red (630 nm): 1 red (660 nm) ; and 2 blue (460 nm): 1 red (630 nm): 1 red (660 nm), respectively. Subsequently, the plant's photosynthetic rate, growth, and morphology depend on the ratios of red and blue light used in the photosynthetic process (Kang *et al*., 2016). Previous research confirmed that red and blue light was effective in various plant productions, including lettuce. Red light is important for plant stem elongation and plant photosynthesis, while blue light is essential in chloroplast development, chlorophyll biosynthesis, plant stomatal opening and photomorphogenesis (Naznin *et al*., 2019; Gao *et al*., 2022).

Potassium, calcium and magnesium contents

Plants need essential elements, such as nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), iron (Fe), zinc (Zn), and non-essential mineral elements like selenium (Se) for physiological growth (White and Brown, 2010). The artificial light source indirectly influences plant mineral metabolism through the photosynthetic system. The intensity and spectrum of light used to stimulate plant growth significantly affect the levels of nutrients accumulated in plant tissues. When light energy is absorbed by chlorophyll in plants, the carbohydrate synthesis rate, dry matter content, plant size, total transpiration rate, and nutrient absorption are increased. The results of nutrient content cultivated under different artificial light sources are reported in Fig. 6a-c. Plants grown under FL irradiation exhibited the highest K, Ca, and Mg content (14.77±3.08, 4.77±0.92 and 108.14±9.36 mg/g DW, respectively). The K, Ca, and Mg contents were not significantly different between plants grown under bulb and bar LED. The cation mole ratios measured in plants grown under FL irradiation were significantly lower than those measured under LEDs light, depicted in Fig. 6d. Calcium is a key component in plant organelles. It is involved in the formation of tissue cell walls. Therefore, Plant tissue cells are essential in photosynthesis, storage, and water transport (Thor, 2019). Mg ions are involved in various processes in plants, including photophosphorylation, photosynthesis, protein amalgamation, chlorophyll development, phloem stacking, and photooxidation in leaf tissues. In addition, K ions are key ions in several essential functions in plant growth, including cell elongation, protein synthesis and stoma closure.

Stressful conditions affect potassium contents in a range of different mechanisms in plants (Tränkner *et al*., 2018; Mostofa *et al*., 2022). Several pathways are known to persist whereby potassium level can be maintained constant despite the actions of different external



2.29 ± 0.32ᵃ cm	1.74 ± 2.17ᵇ cm	1.16 ± 0.18ᶜ cm	11.19 ± 3.57ᶜ cm	15.82 ± 0.69ᵇ cm	17.42 ± 4.65ᵃ cm

Fig. 5. *Stems (a) and roots (b) of green oak lettuce (Lactuca sativa L.) plants grown using different artificial light sources (FL, bar-LED and bulb-LED)*

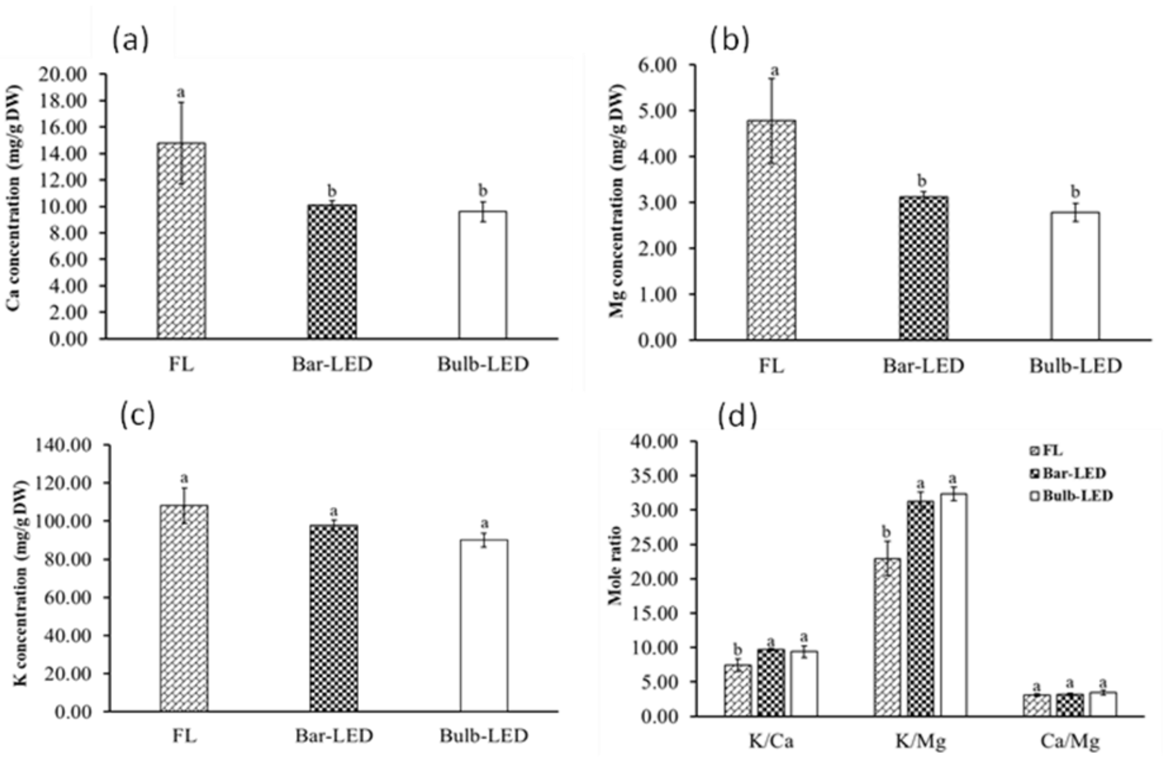


Fig. 6. *Ca^{2+} content (a), Mg^{2+} content (b), K^{+} content (c) and cation mole ratios (d) in green oak lettuce grown under different artificial light sources: FL, bulb-LED and bar-LED*

stressors, for instance the regulation of K^{+} channels, enhancement of water uptake, improvement of reactive oxygen species (ROS) balance and antioxidation. The intensity of the light emitted by bar and bulb-LED were higher than that emitted by FL. High light intensity can increase the photosynthesis rate, boosting ATP production and causing the plant cell wall to undergo remodeling (Li *et al*., 2023). FL, which provides lower light intensity than LED lamps, resulted in insufficient ATP production to remodel the cell wall after ROS-caused damage. Most plants showed Ca^{2+} deficiency due to a lack of cell wall remodeling, which is related to an increase in Ca^{2+} uptake. These results are consistent with those who pointed out that Mg deficiency in wheat and maize was exhibited when the plants were stressed by high heat (Mengutay *et al*., 2013). Mg deficiency in plants has been known to affect ROS production via oxidative stress in cells; degraded chlorophyll can reuse the Mg in chlorophyll to re-form (Sachdev *et al*., 2021).

Plants grown under FL irradiation, which emits lower red-light intensity compared to LED, experienced less heat stress, hence extending their stems toward the FL lamp and tend to increase their Mg uptake to survive. The high intensity of the light emitted by the bulb-LED and bar-LED caused a decrease in the plant K content, which was induced by K leakage (activated by ROS). Several research works have investigated the effect of high light intensity on plant necrosis by reporting the deficiency of potassium in plant leaves (Wang *et al*., 2021). In the present study, irradiation with high-intensity light produced by bulb-LED and bar-LED seems to result in a leakage of K^+ ions triggered by an influx of Ca^{2+} ions into the cytosol due to K^+ deficiency. The uptake of Ca^{2+} was reduced for the survival of the plant. Shabala and Hariadi (2005) reported that Mg availability significantly causes the light-induced changes in net fluxes of Mg^{2+}, H^+, K^+ and Ca^{2+} ions across the plasma membrane of bean mesophyll cells. Pinho *et al.* (2017) also pointed out that the use of light comprising a wavelength spectrum resulting from the combination of far-red, deep-red, and blue LEDs affords maximum plant growth and nutrient uptake indices because the high light intensity effectively increases the rate of photosynthesis, indicating that plants must use a high amount of K^+ ions to balance the charge concentration of the plant cells.

Conclusion

The quality of artificial light generated by bulb-EDs significantly affects green oak lettuce's internode and root length (*Lactuca sativa* L.). The lowest values of internode length and the highest values of root length were observed in lettuce grown under bulb-LED irradiation, which generated blue light at 460 nm and red light in the 630-660 nm range. The intensity ratio of blue and red light in the bulb-LED was blue (460 nm) 2, Red (630 nm) 1, Red (660 nm) 1 and the PPFD values of 44.98 μmol/m^{2}s. The highest K^+, Ca^{2+}, and Mg^{2+} accumulation was observed in lettuce grown under FL irradiation, indicating that using FL controlled the functional components, whereas bulb-LED could control lettuce production in economic trials. Thus, using different artificial light sources and light combinations during the different growth stages of the plant may constitute an efficient system in plant factories.

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Conflict of interests
The authors declare that they have no conflict of interest.

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